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MITIGATION OF EMI/RFI PRODUCED
BY A 1.2 kW
UNINTERRUPTIBLE POWER SUPPLY

by

Efthimios Mikros

September, 1993

Thesis Advisor: Richard W. Adler

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Recently installed equipment in naval receiving sites, such as Uninterruptible Power Supplies (UPS), digital telephone switching systems, and personal computers, inject noise into receiver systems via power conductors, cable shields, and grounds, thus reducing the probability of intercept of a signal of interest, in the 2-100MHz range. In this thesis a survey of EMI/RFI sources at receiving sites is performed. The effectiveness of a Barrier-Filter-Ground architecture in containing/eliminating EMI/RFI from a 1.2 kW UPS is tested. The spectral and temporal properties of the EMI/RFI from the UPS are recorded, estimates for the EMI/RFI power are obtained from 60Hz to 100kHz, and a possible solution is proposed for obtaining noise power estimates for higher frequencies.

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MITIGATION OF EMI/RFI PRODUCED BY A 1.2 kW UNINTERRUPTIBLE POWER SUPPLY

by

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ABSTRACT

Recently installed equipment in naval receiving sites, such as Uninterruptible Power Supplies (UPS), digital telephone switching systems, and personal computers, inject noise into receiver systems via power conductors, cable shields, and grounds, thus reducing the probability of intercept of a signal of interest, in the 2-100MHz range. In this thesis a survey of EMI/RFI sources at receiving sites is performed. The effectiveness of a Barrier-Filter-Ground architecture in containing/eliminating EMI/RFI from a 1.2 kW UPS is tested. The spectral and temporal properties of the EMI/RFI from the UPS are recorded, estimates for the EMI/RFI power are obtained from 60Hz to 100kHz, and a possible solution is proposed for obtaining noise power estimates for higher frequencies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

Electromagnetic Interference (EMI), caused by both internal and external noise sources, can severely limit the performance of receiving sites. A signal originating from a distant transmitter may be degraded by EMI to such an extent that information contained in the signal is partially or completely lost.

Electromagnetic interference can be classified in terms of the way it travels as either radiated or conducted. Radiated interference is unwanted electromagnetic energy that emanates from any equipment, cable, or interconnecting wiring. Radiated interference can be received by a site's antenna along with desired electromagnetic (EM) signals [Ref. 1]. Conducted interference travels from one piece of equipment to another by external conductors. [Ref. 2:p. 1]

In order to reduce the effects of EMI on sensitive electronic equipment like radio receivers, different approaches have been considered for years. The conclusions of those approaches can be summarized as follows:

1. Try to suppress the noise at its source.
2. Make the coupling path as inefficient as possible, by placing a "break" in the path between the noise source and the equipment.

3. Make equipment that can be affected by EMI less susceptible to interference, in other words make the equipment Electromagnetically Compatible.

Among the different techniques that have been developed, the one that has proven to be the most successful at reducing both conducted and radiated EMI effects on sensitive equipment, is to place either the noise source or the equipment inside an electromagnetically shielded barrier. This technique is known as the topological approach to the control of EMI. The barrier is designed in such a way as to achieve broadband electromagnetic separation between the source of interference and the equipment to be protected. The topological approach uses an integrated Barrier, Filter and Ground (BFG) plan for the reduction of the effects of EMI. Grodek [Ref. 3] and Ingram [Ref. 4] examined the effectiveness of a BFG housing in their theses. The conclusion of their work is that, using a BFG plan, excellent isolation between the noise source and the equipment can be achieved over a wide frequency range.

Major internal noise sources can be all kinds of equipment that make use of switching devices, such as Uninterruptible Power Supplies (UPS), power frequency converters, computers and digital telephone switching systems. Switching systems produce wideband Radio Frequency Interference (RFI) and, as they are part of mission oriented equipment, this RFI cannot always be easily eliminated.

Uninterruptible power supplies can be found in every receiving site and their power capacity varies according to use. Interference produced by a UPS is directly proportional to its power. In this thesis the characteristics of EMI/RFI produced by a 1.2 kW UPS will be examined. The main objectives are:

1. To define the primary temporal and spectral properties of EMI produced by the UPS from 0 to 50 MHz.
2. To obtain estimates of the harmonic Volt-Amperes (V.A.) of EMI produced by the UPS.
3. To compare measured values of EMI with the proposed maximum limits for receiving sites.
4. To make an effort to obtain broadband voltage and current RMS values, for estimating the broadband EMI power (V.A.) produced by the UPS within selected frequency ranges.

Chapter II provides the theoretical background required to understand the nature of EMI/RFI. This chapter presents information about different kinds of noise, concentrating mainly on interference produced by switching systems. Chapter IIV describes implementation of an integrated BFG plan. Chapter IV describes the experimental setup, test procedures and instrumentation used. Chapter V deals with the lower part of the frequency region of interest whereas Chapter VI examines the high frequency EMI/RFI characteristics. Finally Chapter VII concludes with a discussion on the benefits,

concerns and recommendations reached from the laboratory research.

II. THEORETICAL BACKGROUND

A. INTRODUCTORY REMARKS

In order to improve the ability of receiving sites to process data, a wide variety of digital, computing, and electrical equipment has been added to those sites over the past years. Widespread use of this equipment, with no concern for the EMI/RFI due to the close proximity of the devices, may result in the degradation of the ability of a receiving site to receive and process data from Signals-of-Interest (SOI's). In addition, external radio noise levels have been increased by encroachment of electrical equipment into the near vicinity of receiving sites, also adversely affecting site performance. [Ref. 5]

B. EXTERNAL NOISE

External noise can be considered as any unwanted or extraneous signal which enters the RF-Distribution System of the site via the antenna. Primary distant external noise sources are natural noise sources , out-of-band Industrial, Scientific and Medical (ISM) transmissions, Electromagnetic Pulses (EMP), as well as any kind of unauthorized radio transmissions [Ref. 5]. From distant sources noise may travel long distances using the same ionospheric propagation paths followed by HF signals.

External noise sources physically close to receiving sites include emissions from sources associated with power lines, out-of-band ISM, gasoline-engine ignition systems, and industrial processes. Nearby external noise is in general a function of the location of the receiving site. [Ref. 5] A brief description of the noise sources mentioned above is provided below.

1. Natural noise sources

Natural sources of EMI/RFI can be further classified as terrestrial, emanating on or near the surface of the earth, or nonterrestrial, emanating from cosmic or solar bodies. [Ref. 2]

a. Terrestrial sources

Terrestrial sources of EMI/RFI include atmospheric lightning discharges, along with radiated fields and part of their energy in the form of whistlers, and local sources such as precipitation static from sand, dust and rain storms. [Ref. 2]

Thunderstorm cell lighting discharges are considered to be a predominant source of EMI/RFI over a very wide frequency range from extremely low frequencies (ELF) up to about 50 MHz. Atmospheric noise amplitude is higher at low frequencies, especially at frequencies below 100 kHz.

Whistlers that travel along the lines of force of the magnetic field of the earth for great distances, are a

small portion of the very low-frequency (VLF) radiation produced by intense lighting discharges.

Precipitation static from sand, dust and rain storms are local natural sources of EMI/RFI. Charged rain drops impinging on conducting surfaces electrically isolated from ground can generate precipitation static. Charge buildup results in corona discharges at sharp projecting points, with the most intense noise occurring when the points are negatively charged with respect to the surroundings. Wideband noise is produced by the corona discharge. During dust or sand storms, particles exchange charge with nearby conducting or dielectric surfaces, resulting in corona discharges as in precipitation static.[Ref. 2]

b. Nonterrestrial sources

Cosmic or galactic background noise (which is radiation from outer space), solar noise, and to a lesser extent photon noise, are main forms of EMI/RFI originating from nonterrestrial sources.

Cosmic noise is radiated from hot gases of stars and by matter distributed in interstellar space. This noise is also a function of frequency, decreasing in amplitude with increasing frequency. Cosmic noise is likely to be a major contributor to total system noise in the very high-frequency (VHF) region (below 300 MHz). It is usually a minor factor above 1 GHz.

The sun is a predominant source of nonterrestrial noise, generating both thermal and nonthermal noise. A normal, or quiet sun, emits thermal radiation covering the whole RF spectrum. At frequencies above 10 GHz, the surface of the sun, whose absolute temperature is about 6000° K, emitts essentially blackbody radiation. At high frequencies, the hotter outer layers are the primary sources of radiation. Solar noise levels are summarized in Figure 1. The curve for the disturbed sun represents maximum probable values, but not record maxima. [Ref. 2]

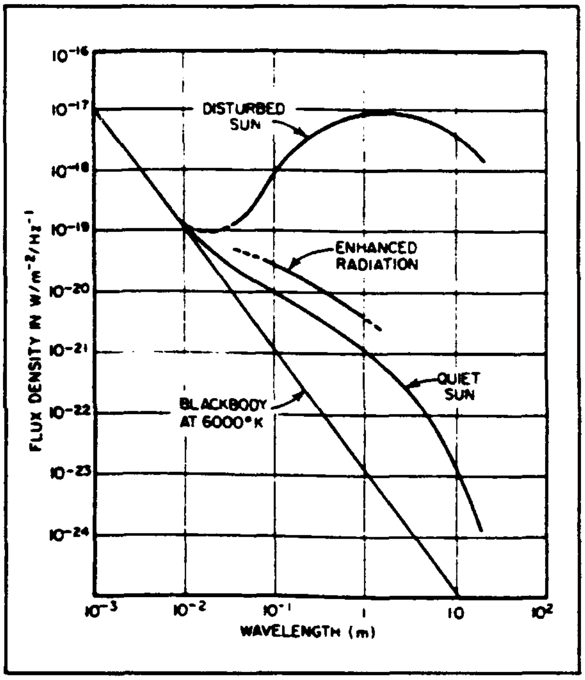


Figure 1. Representative solar noise levels [Ref. 2]

Photon noise is associated with electron transitions in the outer shells of atoms, but has a negligible contribution to radio noise below 50 GHz.

2. ISM transmissions

Industrial facilities within line of sight of a receiving site that use radio-frequency heating equipment in the Industrial, Scientific and Medical service (ISM), may cause severe interference to a site. The operation of ISM

equipment is authorized within the band defined by 27.120 MHz ± 163 kHz. This band is shared with Citizen Band users. Since ISM equipment is frequently operated outside the assigned band (out-of-band ISM signals) in order to have higher efficiency and not to interfere with the Citizen Band, band-stop filters are not always effective for mitigation of ISM EMI. [Ref. 5]

3. Electromagnetic Pulse (EMP)

Electromagnetic pulse is a product of nuclear detonations. It produces very intense transient electric and magnetic fields with very short rise times from 0 to 100 MHz.

4. Power-line noise

Any power line that is within line-of-sight of the uppermost part of a receiving antenna (regardless of distance from the antenna), is a potential source of EMI to receivers connected to the antenna. Power-line noise is usually random in behavior because of the erratic operation of the power line noise sources. The most important examples of noise from sources associated with power lines are gap noise, hardware noise, lightning arrester noise, noise from cable head sparking, and corona noise.[Ref. 6]

Gap noise is the most common type of power-line noise. It is generated when two pieces of metal in physical contact with each other become electrically separated by a thin layer of insulating oxide. The two pieces of metal are charged to

different potentials by the electric field surrounding nearby power conductors. When the potential difference exceeds the breakdown level of the oxide layer, an impulse of current flows from one piece of metal to the other. The potential difference between the two pieces of metal is equalized by the current flow and the discharge process is halted. This process is repeated until the electric field from the nearby conductor decreases to a low level.

Typical sources of hardware noise are loose hardware, loose guy wires, two items of metal near a power line that are in incidental contact with each other, loose connections in the power line conductors, etc. Most hardware-associated noise sources are caused by electrical breakdown of layers of oxide or corrosion.

Sparking can occur at improperly assembled or dirty cable heads used to transition from overhead power conductors to underground power cables. It occurs between the hot conductors and the underground cable shields.

Corona noise is generated when air surrounding an electrical conductor at high potential becomes ionized. Ionization occurs whenever the potential gradient of the electric field surrounding the conductor exceeds the breakdown potential of air.[Ref. 6]

5. Ignition system noise

Automobile ignition systems produce EMI/RFI from 500kHz to 600MHz. Voltages from 5 kV to 15 kV are built up across gaps of spark-plugs, resulting in a spark of short duration and high energy. During this period, a strong radiation field is produced, causing interference whose amplitude is higher at low frequencies.[Ref. 7]

C. INTERNAL NOISE

Internal noise originates within a receiver site. Internal noise sources can fall in two categories: the microscopic noise sources, which have to do with those microscopic mechanisms that produce noise at the atomic level, and circuit components and electrical or electronic devices, which are inherently noisy due to their operating characteristics and microscopic effects. A brief survey of internal noise sources follows.

1. Microscopic sources

The most commonly encountered types of noise in this category are thermal or Johnson noise and shot noise. Thermal noise arises from random velocity fluctuations of charge carriers (electrons and/or holes) in a resistive material. Shot noise is associated with the passage of current across a potential barrier such as the depletion layer of a p-n

junction, and it is frequently encountered in solid-state devices. [Ref. 8]

Generation-recombination noise, which along with Johnson noise, dominates in JFETS, is caused by random trapping of charge carriers in semiconductor materials. Flicker noise or 1/f noise is also in this category. It occurs in a wide variety of systems but particularly in solid state devices.

Another type of noise produced at the atomic level is burst noise which is electrical noise in the form of random "bursts" occuring in different types of solid state devices such as p-n diodes, tunnel diodes and transistors . Burst noise in reverse-biased p-n junctions is due to irregular on-off switching of a surface channel. Burst noise in forward biased junctions is due to defects in the vicinity of the junction. [Ref. 8]

2. Circuit components and devices

Beyond microscopic noise sources, most circuit components and electronic devices are inherently noisy. Examples of circuit components used extensively and causing considerable amounts of EMI/RFI, are all kinds of mixers (single balanced, double balanced, balanced-bridge switching) and oscillators (Tunnel diodes, Impatts, and Gunn diodes). Signal processing operations such as modulation/demodulation, heterodyning, limiting and detection, in addition to "useful"

output, produce intermodulation and crossmodulation products, in other words: EMI/RFI. The noise which is a product of those operations is due to circuit component non-linearities.

Examples of devices acting as internal noise sources include transmitters, signal generators, antenna switching systems as well as any kind of equipment that makes use of switching (computers, UPS, telephone switching systems, etc.). Figure 2 lists some common noise sources, narrowband and

Broadband			Narrowband	
Transient	Intermittent	Continuous	Intermittent	Continuous
Mechanical Function switches Motor starters Thermostats Timer units Thyratron trigger circuits	Electronic computers Motor speed controls Poor or loose ground connections Arc Welding equipment Electric Drills	Commutation noise Electric typewriters Ignition systems Arc and vapor lamps Pulse generators Pulse Radar transmitters Sliding contacts Teletype-writer equipment Voltage regulators	cw-Doppler radar Radio transmitters and their harmonics Signal generators, oscillators and other types of test equip-ment Transponders Diathermy Equipment	Power-line hum Receiver local oscillators

Figure 2. Typical man-made noise sources [Ref. 9]

broadband. Switching devices are major contributors to internally generated noise. Transitions between the two states (switching) tend to be extraordinarily fast (pulse

rise/fall times of order 1-20 ns). These transitions generate high frequency spectral components which can be conducted and/or radiated from the device or conductors associated with the device. [Ref. 10]

Internally-generated noise enters the Radio Frequency (RF) distribution system of a site in various ways. These include the leakage of ambient EM signals into system cables and components, inductive coupling from one conductor to another, and direct conduction through grounds, power cables, and coaxial cable shields.[Ref. 5]

D. UNINTERRUPTIBLE POWER SUPPLY (UPS)

Uninterruptible power supplies, whose power capacity varies according to the systems or devices they support, are used extensively in receiving sites. A UPS rectifies incoming AC line current in a switching regulator to charge batteries. The DC current from the batteries is then converted into a 60-Hz "pseudo-sine wave" using a static inverter. The inverter "steps" the voltage up and down in increments at a rate of 60 Hz, then passes the output to a low-pass filter which removes many of the high-frequency components. It is the switching, which occurs during rectifying and inversion, that generates noise on both the input and output conductors of a UPS. Switchers are extremely noisy. Their outputs have tens of millivolts of switching ripple, they put noise onto the power line, and they can even scream audibly [Ref. 11].

III. BARRIER-FILTER-GROUND PLAN

On-going research is being conducted by the Signal-to-Noise-Enhancement Program (SNEP) in the area of EMI/RFI control at Circularly Disposed Antenna Arrays (CDAA) receiving sites. Specific noise sources have been identified and different techniques have been developed in order to minimize the effects of EMI/RFI. One technique for the control of EMI/RFI, is the topological approach.

The topological approach to interference reduction uses an integrated barrier, filter and ground configuration to minimize the effects of EMI/RFI on a receiving or other system. The primary functions of a BFG configuration are:

1. To prevent EMI/RFI generated within an electrical device from leaving the enclosure.
2. To prevent EMI/RFI generated by devices located outside an enclosure from entering the enclosure.
3. To meet all electrical safety requirements of a site.[Ref. 5]

Figure 3 illustrates an example of a BFG architecture where the noise source is a UPS. The barrier in the topological approach is a conductive enclosure which shields the enclosed equipment from ambient EM energy, and also contains the EM energy emitted by the equipment.

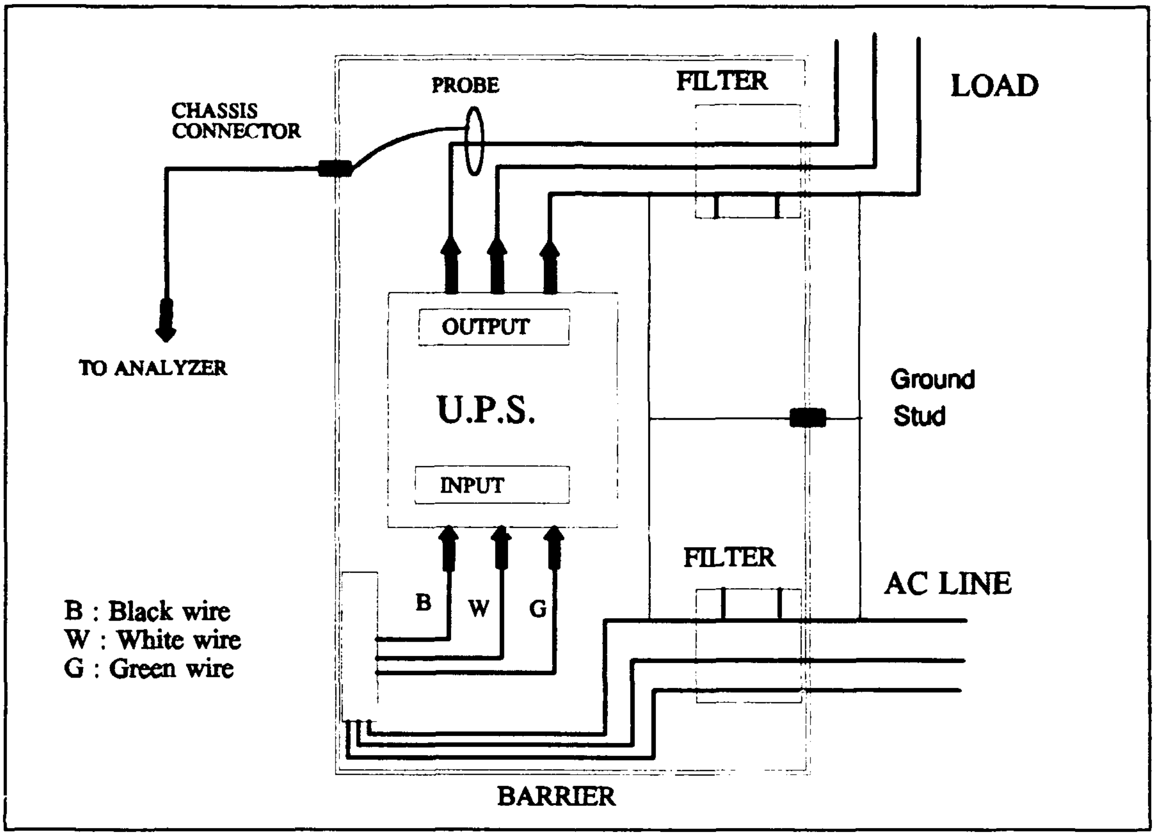


Figure 3. Barrier, Filter, Ground architecture

A barrier need not be a complete solid enclosure, that is to say that modest sized doors without EM seals as well as holes on the surfaces of the cabinets, are permissible at HF. Based on Babinet's principle[1], one could claim that openings on the surfaces of the cabinet could act as aperture antennas, meaning that fields interior to the barrier will radiate through these openings. Recalling that Babinet's principle is

[1]Babinet's principle states that a slot in an infinite perfectly conducting plane and an isolated strip are "dual problems". A consequence of this principle is that apertures can be as effective radiators as antennas whose conductor dimensions are those of the aperture [Ref. 10].

valid only in the far-field region where plane waves are assumed, the inner limit of the far-field region for a UPS, which is the source of the radiated EM energy (EMI/RFI), must be calculated from 0 to 100 MHz. At 100 MHz the corresponding wavelength is $\lambda=3$ m and the far-field region starts at a distance about 9 m (about three times the wavelength for small sources) from the source. So, for the case of a UPS installed in a cabinet, the openings are not in the far-field of the noise source. The distance between the surfaces of the metallic enclosure and the UPS is very small in wavelengths. Since openings on the cabinet walls would be within the reactive near field of the source, radiation impinging on the openings is not in the form of plane waves, and Babinet's principle does not hold. Thus, it becomes clear that the use of the term "barrier" in a BFG architecture at the cabinet level, does not strictly refer to the control of radiated EMI/RFI by means of the shielding theory (thoroughly described in Ref. 10). The term "barrier" stands for a means of controlling the EMI/RFI current flowing on all conductors penetrating the cabinet walls, as well as on the walls themselves.

A primary and necessary feature of a barrier is that no uncontrolled conductor can penetrate a barrier. The electrical properties of all conductors penetrating a barrier must be strictly controlled. Signal conductors required for use by the enclosed equipment, as well as equipment outputs, must be

EMI/RFI controlled by using shielded cable. Inductively-coupled noise is restricted to the surface of the shield enclosing the conductor. Shielded cable penetrations of barriers must be made by means of bulkhead connectors.

Ground cables must be connected to barriers by use of ground studs. A ground stud is used to bond the exterior ground to the exterior surface of the barrier, and the interior ground to the interior surface of the barrier (Fig. 3). The installation of a ground stud, which is in direct contact with the internal and the external surfaces of the enclosure, provides:

1. A path for internally generated EMI/RFI current to return to its source without exiting the controlled space.
2. A return path for externally generated noise current to return to its source without penetrating into the controlled space.[Ref. 5]

Power conductors that supply electrical power, must be controlled so that they conduct electrical power through the barrier but not conduct EMI/RFI across the barrier. Low-pass power-line filters must be used to prevent the flow of EMI/RFI across the barrier. The filters must provide a low-impedance path for internally-generated noise and signal currents to return to their sources within the enclosure. The filter must also provide a high-impedance path to inhibit the flow of EMI/RFI current across the barrier. It must also have

a low-impedance path for externally-generated EMI/RFI current to return to its source without penetrating the barrier, and a high-impedance path to prevent the EMI/RFI current from flowing into the controlled space. [Ref. 5]

A single topological layer, as illustrated in Figure 3, can provide 30 to 50 dB, or more, of noise isolation. The isolation can be enhanced by the use of subsequent layering of barriers.

IV. EXPERIMENTAL PROCEDURE

A. GENERAL SETUP

The test measurements were all made with off-the-shelf equipment either at the Microwave Laboratory, Room 419 Spanagel Hall, or on the roof of Spanagel Hall, Room 603, Naval Postgraduate School. A 1.2 kW UPS was placed inside a standard equipment cabinet with a front door, whose rear face was closed by a conducting plate in perfect electrical contact with the cabinet. Two metal-encased low-pass power-line filters (input-output) were mounted on the rear plate using metal screws, insuring a metal-to-metal bond. The plate was mounted so that the filters were located physically inside the cabinet. The use of bulkhead connectors ensured that the shielded signal cables penetrating the barrier were EMI/RFI controlled. A purely resistive load was connected to the output of the UPS. The experimental setup strictly followed the principles of BFG architecture, as described in Chapter IIV.

B. INSTRUMENTATION

The experiments included EMI/RFI current and voltage measurements on power-line conductors, within selected frequency ranges. The lower part (0 - 100 kHz) of the frequency region of interest (0 - 100 MHz) is considered separately,

due to the limited frequency range of the HP 3561A FFT signal analyzer used.

1. Low frequency instrumentation

The primary low-frequency instrumentation includes a Tektronix CT-4 High Current Transformer (used in conjunction with the P6021 AC current probe), a Tektronix (10:1) termination, an HP3561A Dynamic Signal Analyzer, a variable gain (40 dB in 10-dB steps) low-frequency line amplifier, and a Tektronix 2445B oscilloscope. This instrumentation can accurately measure current and voltage in any conductor over the frequency range of 12 Hz to 100 kHz.

The CT 4 is a pistol-grip type current clamp with a frequency range of 25 Hz to 20 MHz when used with the P6021 probe. The P6021 current probe with its termination converts either two or ten milliamperes of current into one millivolt at the oscilloscope input (2mA/mV or 10mA/mV).

Low-level signal measurement capability was increased by a "homemade" line amplifier, which provided adjustable gain in steps of 10 dB. The line amplifier was battery powered in order to minimize the introduction of stray 60-Hz effects and harmonics of 60 HZ from power supplies into the signal measurement path.

The HP3561A is a single-channel, Fast-Fourier Transform (FFT), signal analyzer covering 0 to 100 kHz and has

high dynamic range (80 dB). Display formats include single traces, two traces, and up to 60 traces in map-type formats.

2. High frequency instrumentation

The primary measuring components of the high-frequency experiments include a Develco Model 7200B 3-Axis Display, HP141T Spectrum Analyzer, Fischer F-70 RF Current probe, model 201D Voltage probe, Boonton RMS meter, and selected filters and RF amplifiers.

The 3-Axis Display provides a unique measuring tool for observing spectral and temporal relationship of noise and signals. Figure 4 [Ref. 4:p. 22] shows an example of stored time history of the analyzer output. This display can be frozen with the present and previous scans stored in memory, and the stored view can be orientated for best viewing and

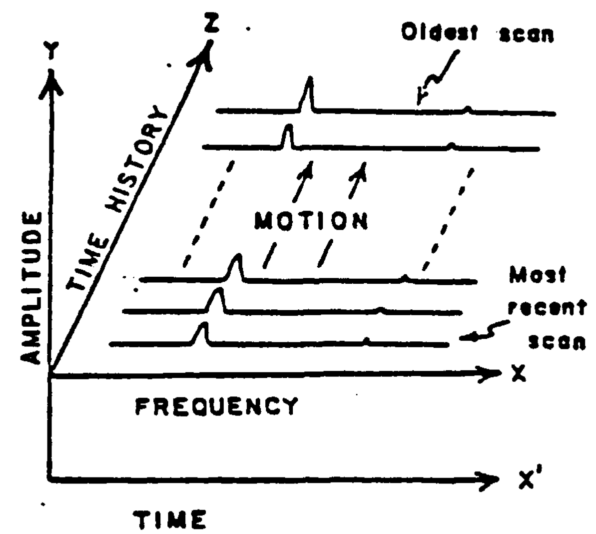


Figure 4. Three Axis Display [Ref. 4]

signal analysis. The 3-axis presentation can be photographed for later analysis.

The HP141T Spectrum Analyzer was used in conjunction with the 8553B RF Section and 8552B IF Section, allowing observation of signals and noise up to 110 MHz.

The Fischer F-70 RF Current probe, was used to measure current flowing on the wires. The output of the F-70, flat above 100 kHz, was amplified by either a 10-dB or a 20-dB RF amplifier, whose output was then fed into the spectrum analyzer. The use of the two bandpass filters, manufactured by TTE, allowed the observation of EMI/RFI at selected frequency regions (100 Hz - 1 MHz and 2 - 30 MHz).

The model 201D Voltage Probe is a high voltage probe with a flat response above 1 kHz (-3 dB at 600 Hz). The incoming voltage signal can be attenuated down to 40 dB, in steps of 20 dB, so that the Spectrum Analyzers, or any other measuring equipment, is not saturated by high-amplitude signals.

The Boonton RMS meter was initially used for broadband RMS current and voltage measurements. Since this is a low input impedance instrument (50-75 Ohms) and the 201D probe has a high output impedance, accurate RMS voltage measurements were not possible with the Boonton RMS meter.

Figure 5 illustrates the experimental setup for both high and low-frequency experiments. All interconnecting signal cables used for the experiments, were double-shielded

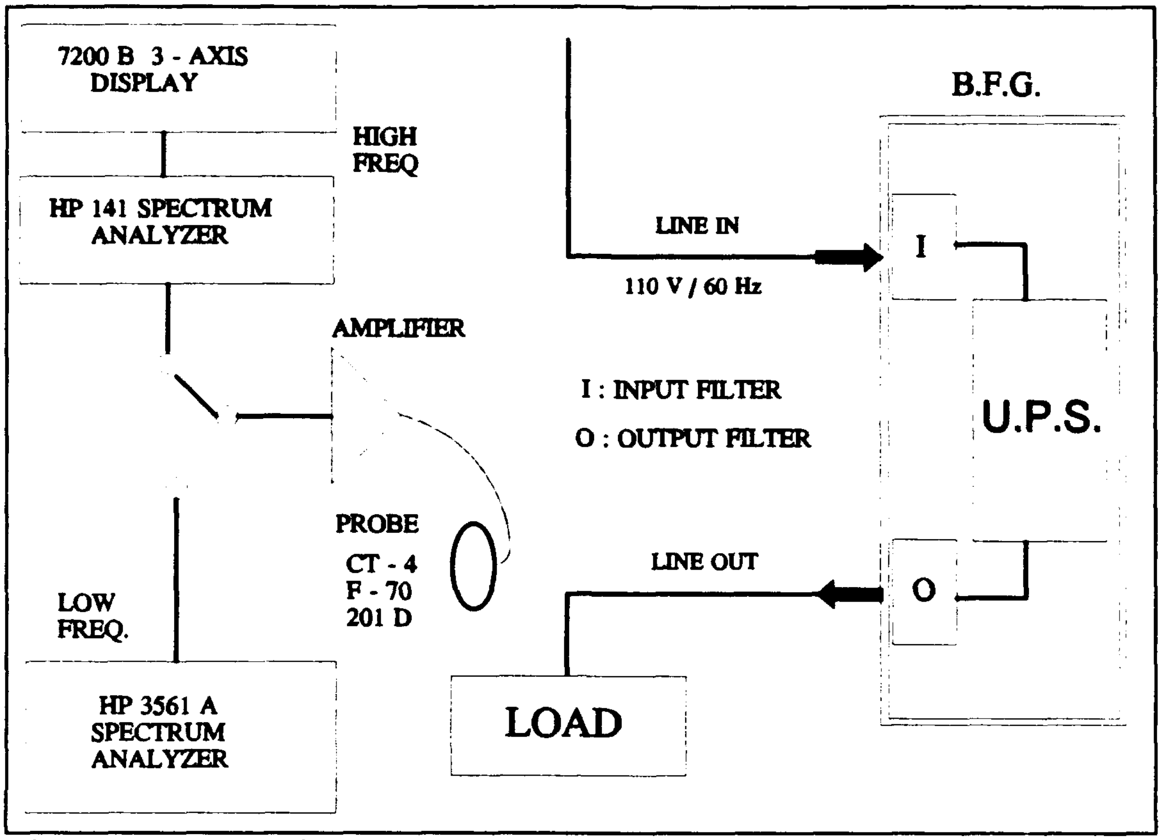


Figure 5. Experimental Setup

RG-223 coaxial cables. A Tektronix C5 polaroid camera was used to obtain time and frequency domain pictures of EMI/RFI. Finally, the use of a stand-alone diesel-powered generator was necessary in order to get rid of an ambient noise problem, as will be discussed later.

C. SPECIAL CONSIDERATIONS

1. Time

Noise is highly time dependent. Conducted noise on the building power-lines is dependent on the activity of many

sources associated with the electrical loads operating at a specific time. The noise observed on building power conductors during working hours is expected to be higher than the noise experienced during non-working hours, simply because more equipment is drawing power and injecting noise into the building power conductors during the normal working days. This is particularly true in the case of Spanagel Hall, Naval Postgraduate School, where the Microwave Laboratory is located. Spanagel Hall contains many Computer Work Stations, Personal Computers (PCs), power conditioning devices, and laboratory instruments in support of the engineering curricula. Laboratory equipment and digital devices, are generators of EMI/RFI, which is spread by conduction along the power-conductors of the building or, by inductive coupling into conduits and other conductors. Consequently, efforts were made to take related data set measurements as quickly as possible to minimize the chance of misinterpreting the results due to changes in the dynamic ambient noise level. As a consequence of the time-dependence of ambient noise, an exact replication of EMI/RFI related experiments is impossible.

2. Ambient noise

Ambient noise, either radiated or conducted, was a major problem while conducting the experiments. Figure 6 illustrates an example of noise generated by a personal computer (486/50 MHz), located in the Microwave Laboratory,

injected into the black power conductor. The frequency range used for the observation was from 0 to 100 MHz, and the computer was placed inside the barrier, isolating it from other EMI/RFI sources. Figure 6 shows the spectral and temporal representation of the current on the black or "hot" wire of the power-line supplying the PC. The top amplitude picture illustrates the case when the CPU is idle and the bottom picture when the CPU is running. In both cases, there is a noise spike at 6 MHz (about 70 μA).

Figure 7 shows noise current on the green wire, when the CPU is idle, and when the laser printer located inside the barrier is printing. Both figures show that digital devices in the computer and the printer are extremely noisy over a wide frequency band. Besides the noise sources within the laboratory, broadcasting activity in the local area (airport and local radio stations) also affected the measurements.

The main problem encountered while taking the outside-the-barrier measurements was the uncertainty whether the observed EMI/RFI originated from the UPS or was ambient noise from sources within the building.

In order to eliminate the EMI/RFI conducted through the building's power-conductors, the low-frequency experiments were repeated on the roof of Spanagel Hall, Room 603, using "clean" power provided by a diesel-powered generator.

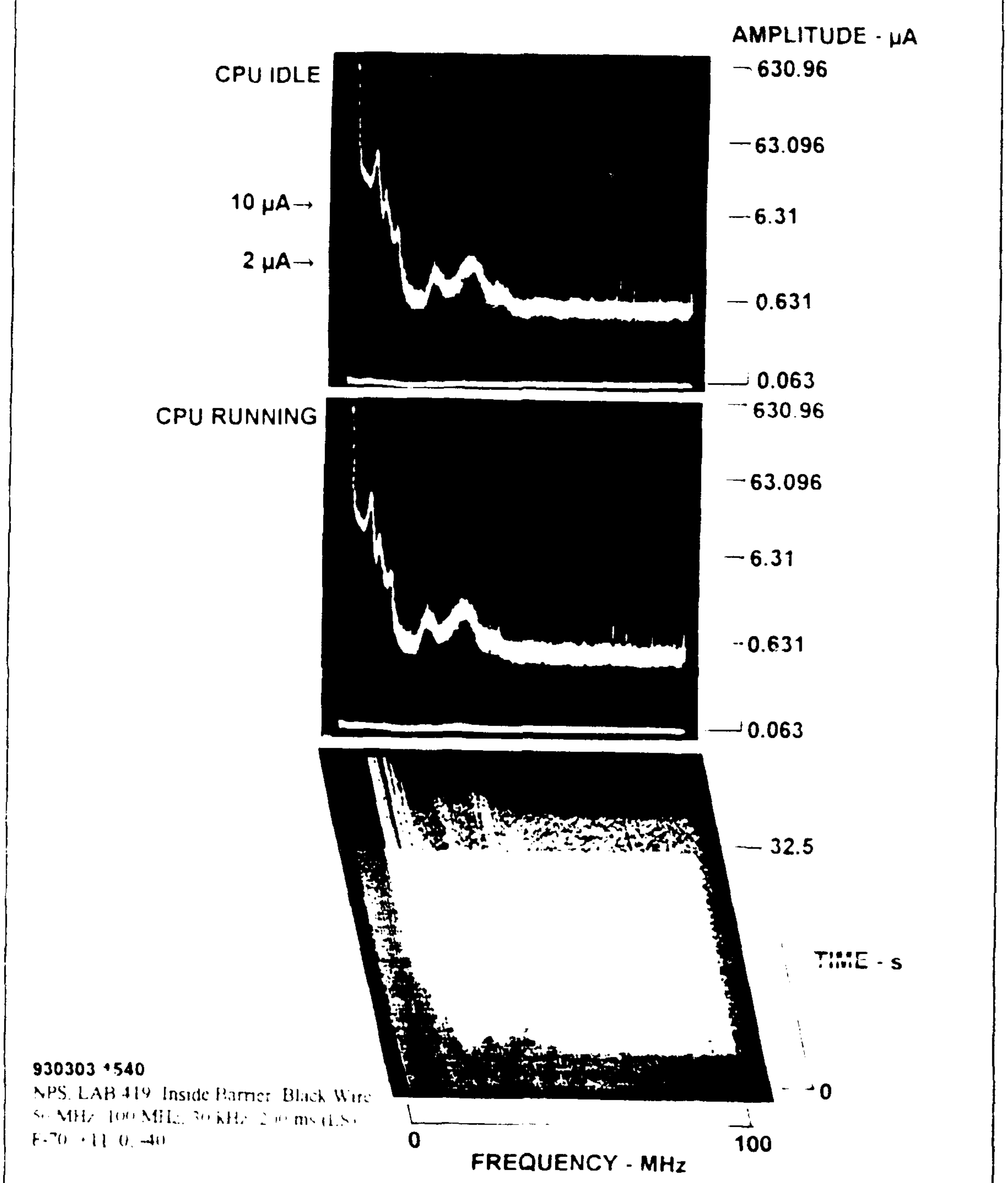


Figure 6. EMI/RFI from a PC-Black Wire

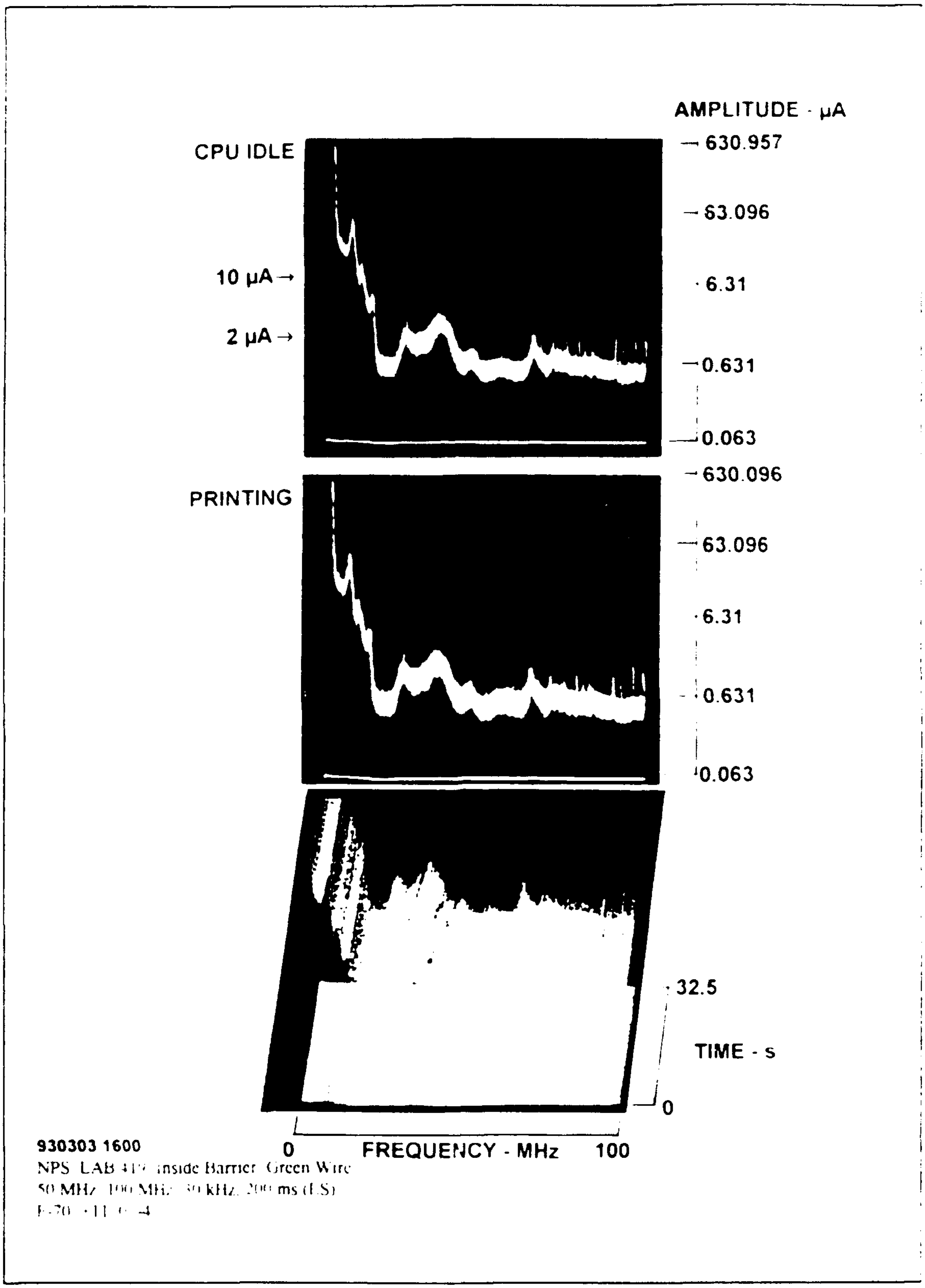


Figure 7. EMI/RFI from a PC-Green Wire

D. INSTRUMENTATION PROBLEMS

There was only one major instrumentation problem during the experimental procedure. The 201D voltage probe, whose frequency response was not flat, failed during the RMS voltage measurements due to an internal short. Since the probe was homemade and the construction and calibration of a new probe would take a considerable amount of time, RMS voltage measurements were not possible. This failure did not allow the derivation of a *broadband RMS noise power* and a *broadband RMS impedance*, whose basic concepts are discussed in Chapter VI.

V. LOW-FREQUENCY EXPERIMENTS

Before starting the low-frequency current and voltage measurements, a test was performed to examine whether the in-band EMI/RFI could be considered as band-limited white noise. White noise is a random process whose power spectral density is constant for all values of frequency ω; that is, $S_x(\omega) = S_0$ [Ref. 13]. Although the concept of white noise is fictitious, if the power spectral density of a noise signal is constant over a finite bandwidth and close to zero outside this frequency range, it can be considered as band-limited white noise. Such an assumption would greatly simplify noise power calculations without introducing any significant error. Since the power spectral density of band-limited white noise is constant over a specific frequency range, the power-bandwidth relationship is linear, with a slope of 3dB/octave. Consequently if noise power in dB is plotted versus bandwidth, the graph will be a straight line. For the purpose of this test, the spectral views for the current on black wire, for both the input and the output of the UPS, were obtained for different IF bandwidths of the spectrum analyzer (3,10,30 and 100kHz). Figures 8 through 14 show EMI/RFI current amplitude at 10, 16, 26, and 32 MHz versus the four different IF bandwidths.

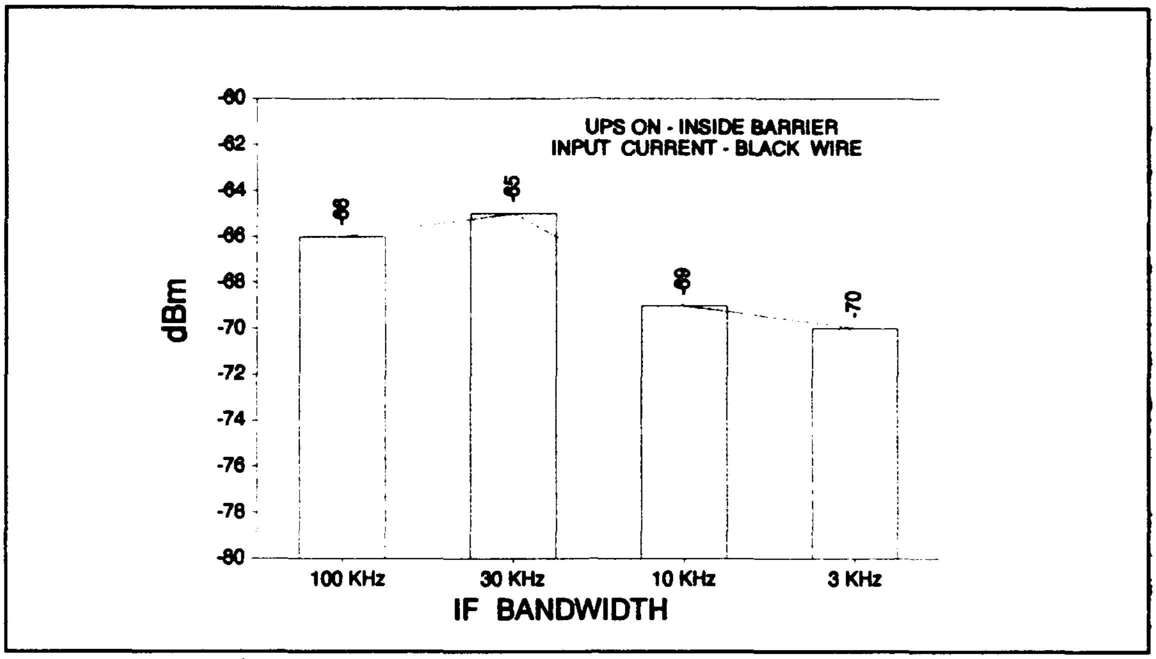


Figure 8. Noise Current vs. IF Bandwidth (10MHz)

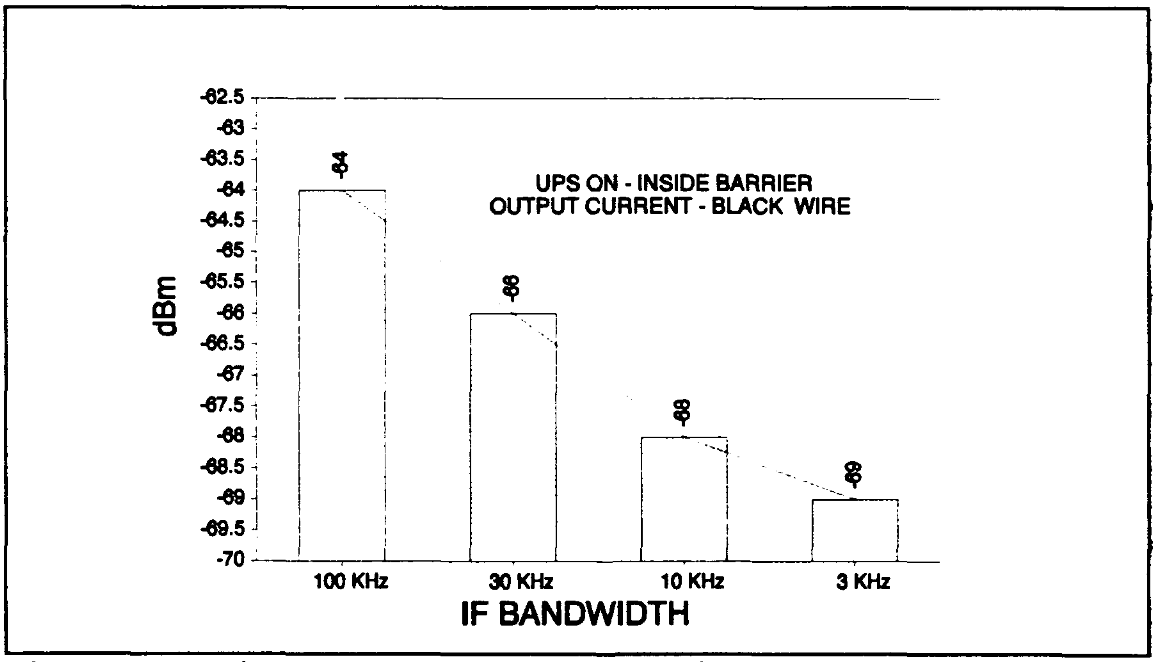


Figure 9. Noise Current vs. IF Bandwidth (10MHz)

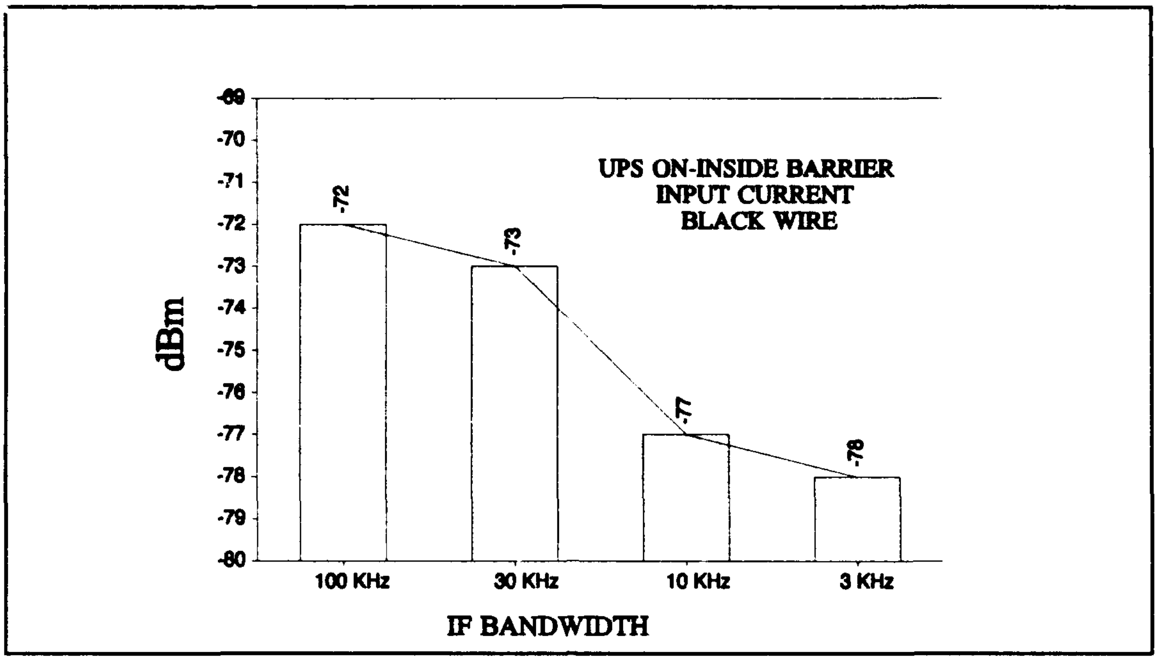


Figure 10. Noise Current vs. IF Bandwidth (16MHz)

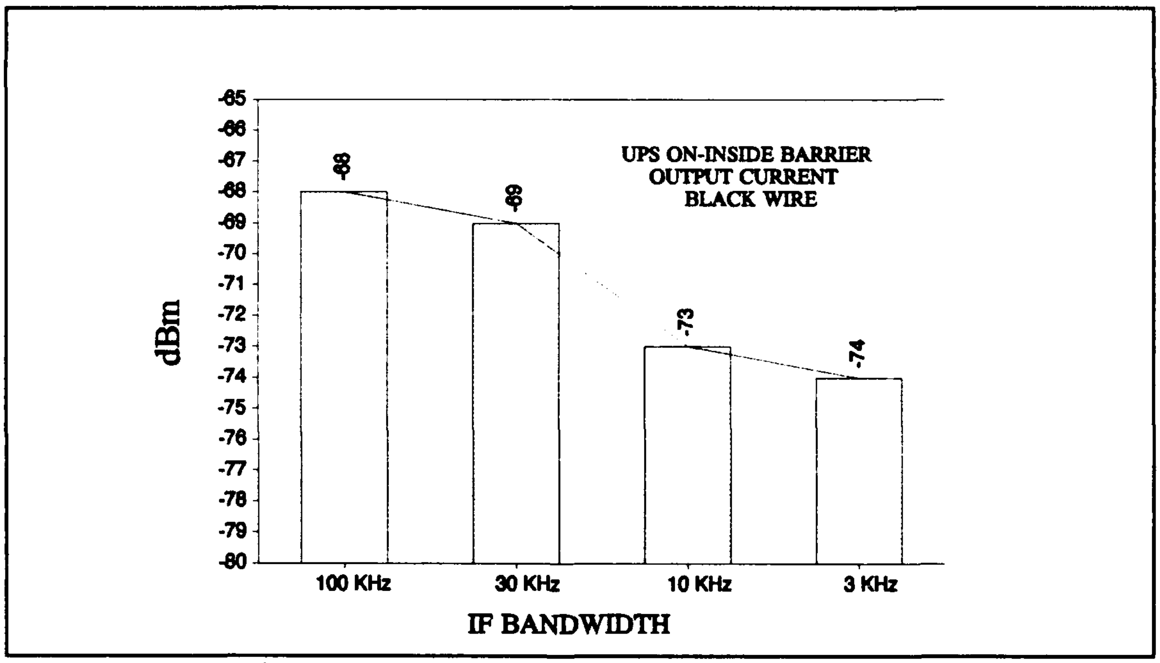


Figure 11. Noise Current vs. IF Bandwidth (16MHz)

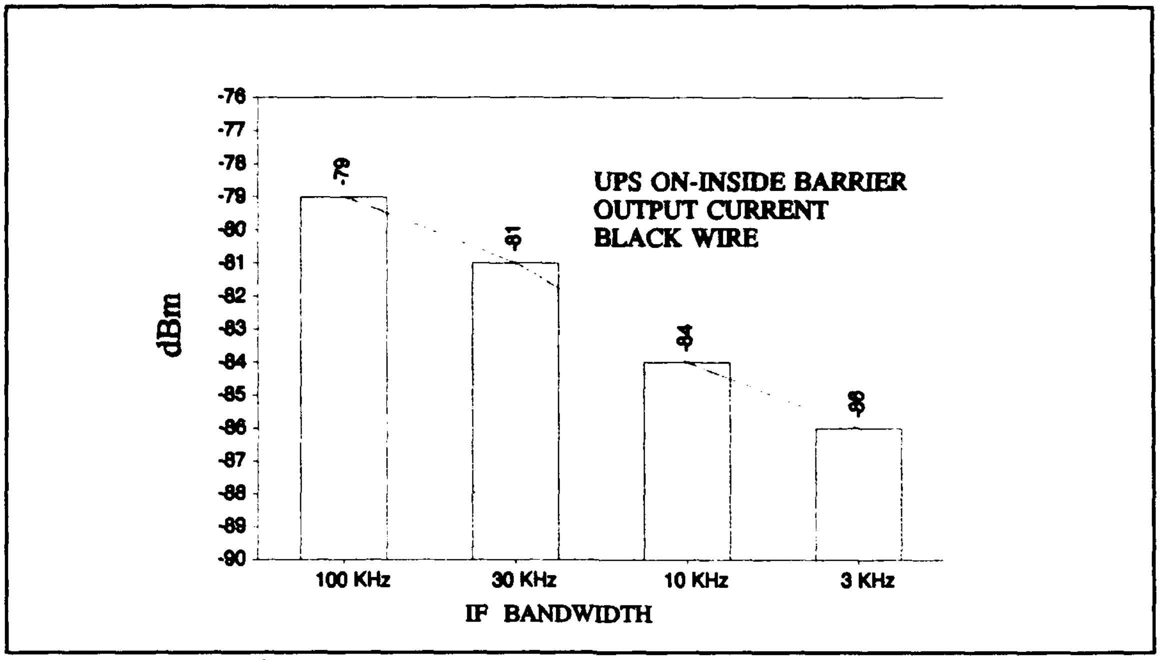


Figure 12. Noise Current vs. IF Bandwidth (32MHz)

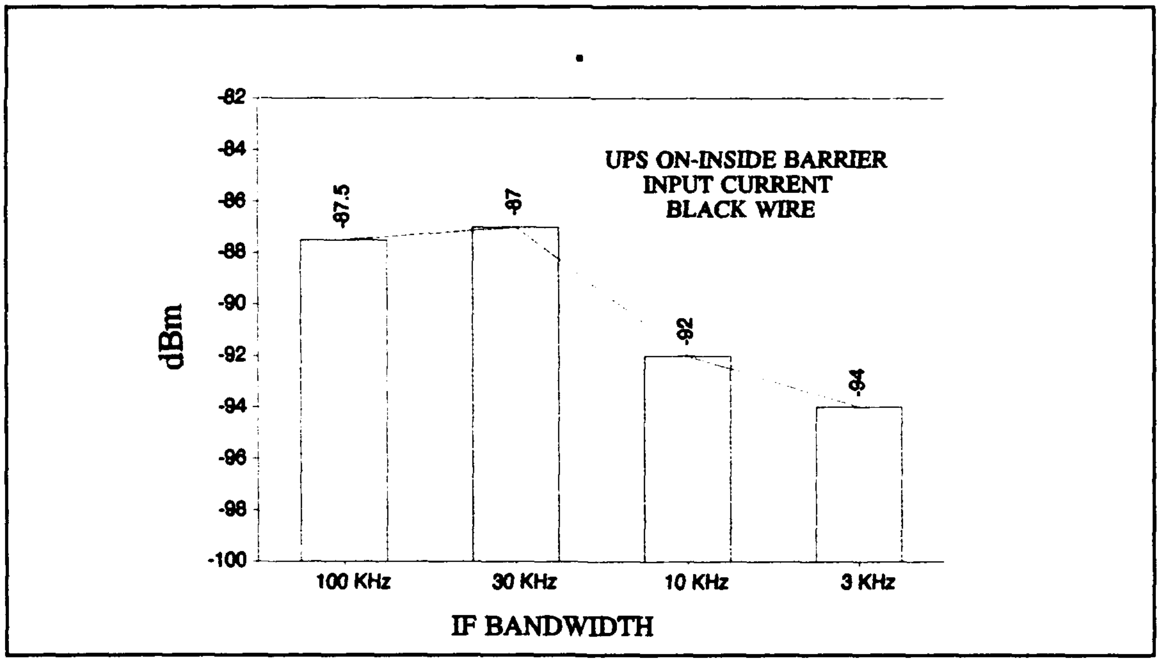


Figure 13. Noise Current vs. IF Bandwidth (32MHz)

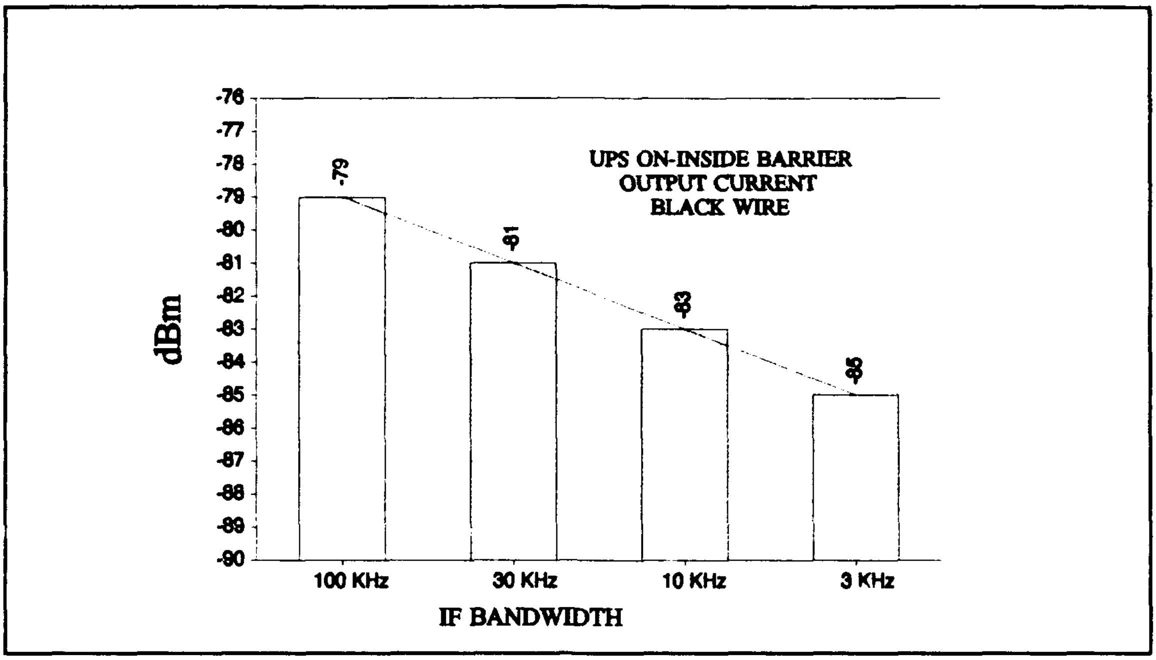


Figure 14. Noise Current vs. IF Bandwidth (26MHz)

It is obvious from the graphs that most of the interference produced by the UPS cannot be considered as band-limited white noise, over the frequency ranges where the test was performed. Figures 9, 11, and 13, which illustrate the noise current at the input versus IF Bandwidth, reveal that at the frequency ranges where the test was performed there is a superposition of EMI/RFI with a continuous wave (CW), the CW dominating. Figures 12 and 14 show two examples where the EMI/RFI level varies linearly with IF bandwidth. A uniformly changing slope with bandwidth is typical of gaussian noise, however the slope of the variation (4dB/decade) indicates that the noise is not gaussian. The temporal shape of these two examples is such that a linear change with bandwidth was obtained over the range examined.

As previously mentioned, the low-frequency band for the measurements extends from 0 to 100 kHz. Voltage and current values were obtained, in order to derive an estimate for the amount of noise power generated by the UPS in this frequency region. The estimated noise power will provide information about the amount of total power that must be dissipated in the filter portion of a BFG. This information is required for the design of power-line filters, especially when higher power UPS units are used.

The low-frequency experiments initially obtained a spectral (0-100kHz) and temporal view of the current on both black and white wires, using the HP141 spectrum analyzer and the 3-Axis display. Both observations, illustrated in Figures 15 and 16, were made at the input of the UPS and inside the barrier while the batteries were charging. Information about the time, date, and place where the pictures were taken, and instrumentation settings are provided in a small chart. The format of the information chart follows.

- Date, time
- Location, Room, Equipment under test
- Observation point, Inside/Outside Barrier, Wire
- Center Frequency, Frequency Span, IF bandwidth, Time Span, Sync
- Probe Setting, Line Amp, Input Attenuation, Reference

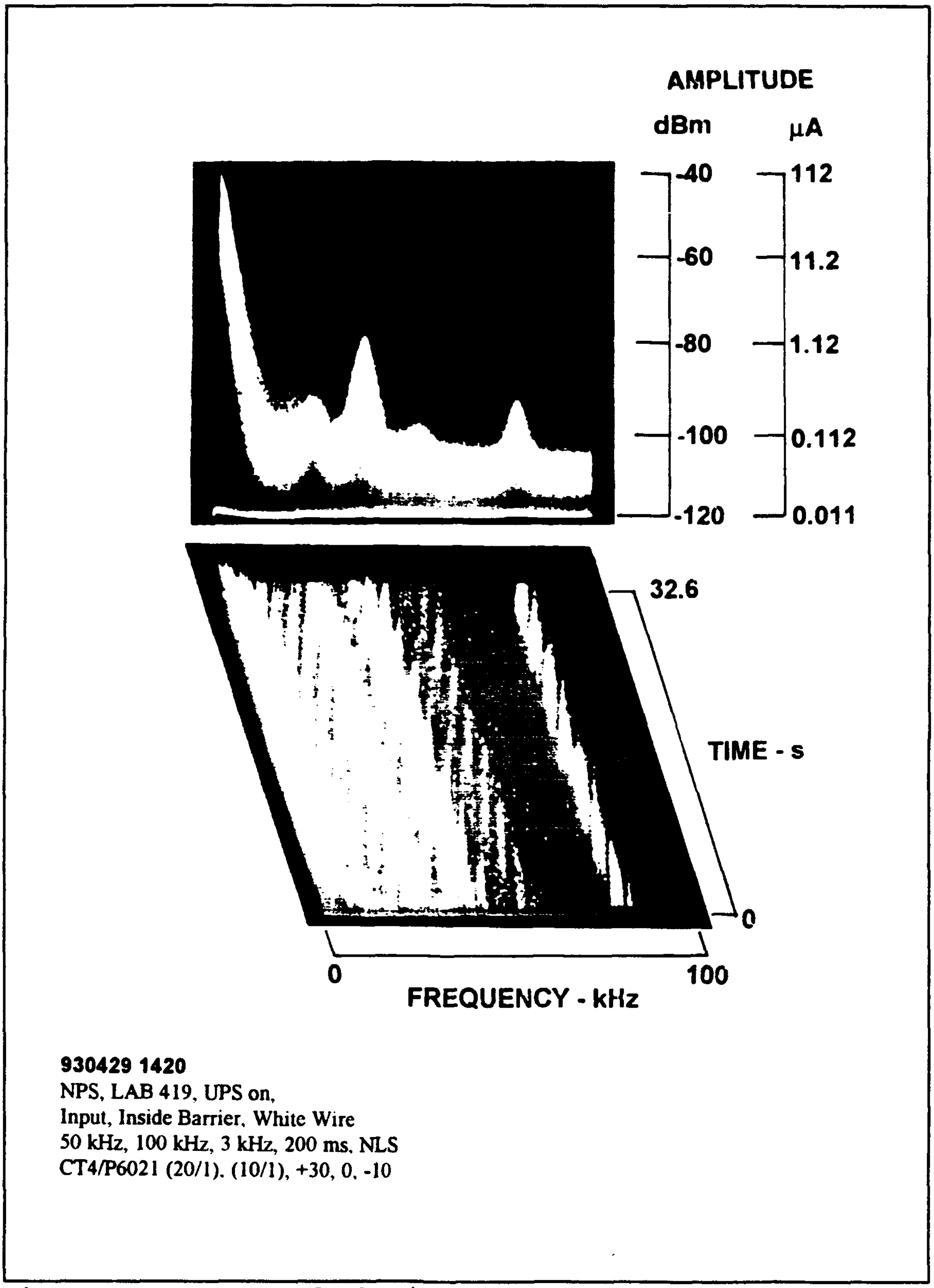


Figure 15. Current-Black Wire-UPS Input(0kHz-100kHz)

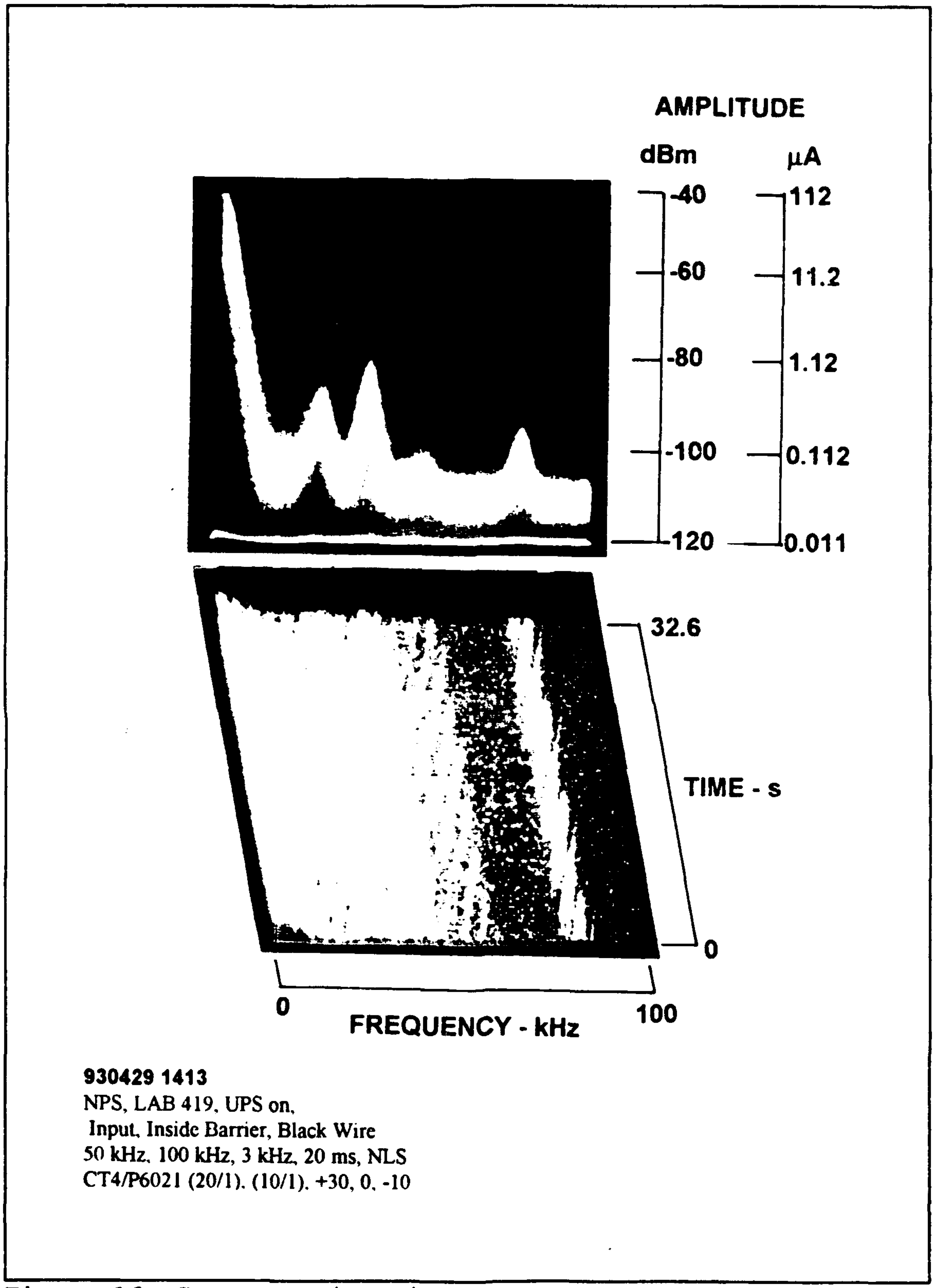


Figure 16. Current-White Wire-UPS Input(0kHz-100kHz)

The black wire and white wire current spectral views are almost the same, as expected. Throughout the thesis, only the EMI/RFI current on black and green wires will be presented. Figures 15 and 16 show that the entire frequency range is contaminated with noise. Since the UPS is isolated from external noise sources, the EMI/RFI is probably produced by the battery-charging function. The current-amplitude pictures show that the noise power is higher at the lower part of the spectrum. In Figure 17, a closer "look" into a noise peak at about 30 KHz is taken by reducing the frequency span of the spectrum analyzer to 23 to 33kHz. The 3-axis view of the current in Figure 17, shows a change in the slope of the slanting lines of noise. This indicates that the period between bursts of noise changed. It is evident that the frequency changes between two values, suggesting that a small instability in the frequency of the EMI/RFI generated by the UPS, occurs when the UPS is loaded.

The second round of experiments included current and voltage measurements from 0 to 100kHz, using the HP3561A FFT signal analyzer. After obtaining current and voltage values, the "total harmonic power" was computed. The UPS was powered from the building's "noisy" power. The ground wire is used as a reference for voltage measurements, although there is EMI/RFI current flowing on all ground conductors, as shown later.

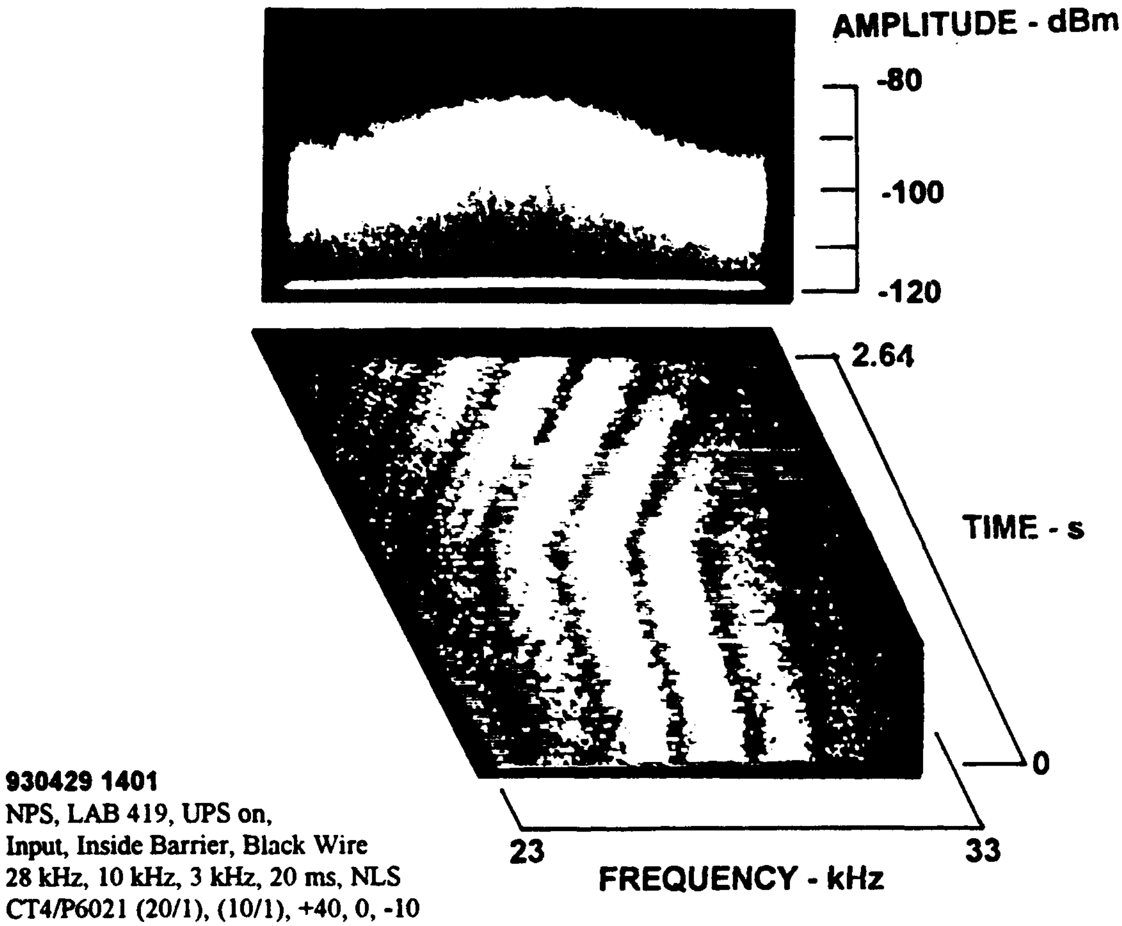
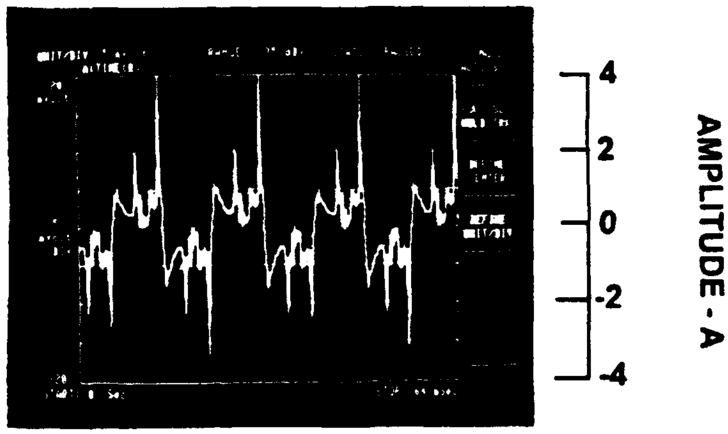


Figure 17. Current-Black Wire-UPS Input(23kHz-33kHz)

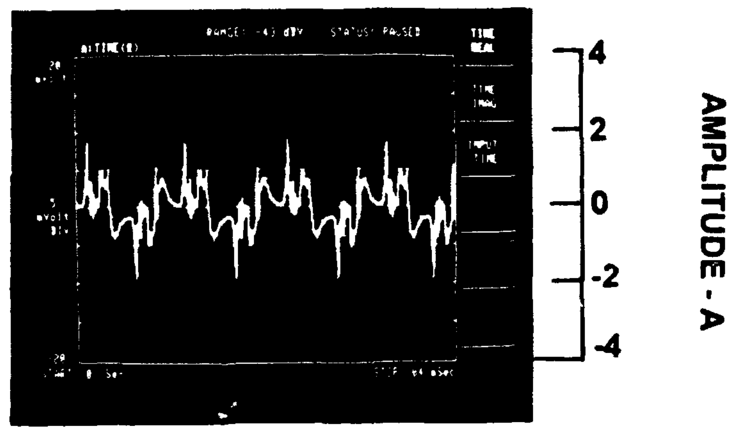
Before starting the measurements, a time domain picture of the current on the black wire, at the UPS input and outside the barrier, was obtained. Two cases were considered; the first case where the UPS was loaded by a purely resistive load, and the second case where no load was connected to the output of the UPS. Photographs of the waveshape for both cases are provided in Figure 18. The current waveform, instead of being sinusoidal, is a periodic signal full of high-frequency components. In other words, the current waveform can be considered as the superposition of a 60-Hz sinusoidal wave with higher frequency EMI/RFI signals originating from various noise sources. The EMI/RFI is conducted and/or inductively coupled into the power conductors, resulting in significant contamination of the the power-line current. At this point, without having yet examined the effectiveness of the BFG over this frequency range, no conclusion can be drawn about whether the EMI/RFI contaminating the current is due to the UPS. Figure 18 also reveals that when the resistive load is connected to the UPS output, the amplitude of the current increases dramatically. In real-life applications, the loads are never purely resistive but always contain some reactance. A reactive load might cause even greater EMI/RFI levels on the power-line conductors. The data show that the EMI/RFI power on the input conductors of the UPS increases as the load increases.

UPS LOADED



930504 1140
NPS, LAB 419, UPS on,
Input, Outside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

UPS UNLOADED



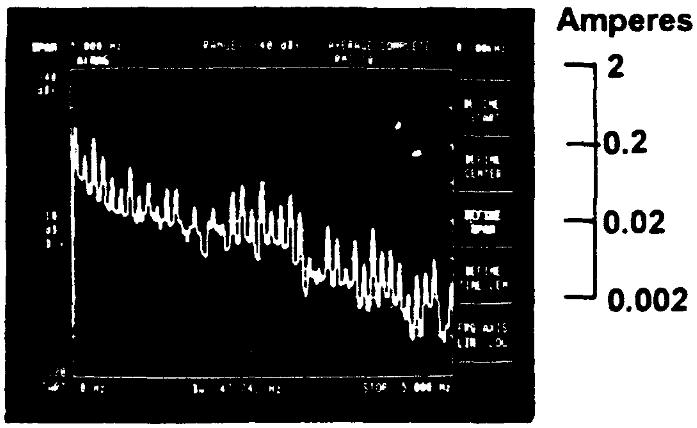
930506 1358
NPS, LAB 419, UPS on,
Input, Outside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

Figure 18. Black-Wire Current Spectrum-Input (0-5kHz)

Using the FFT analyzer, spectral pictures of current and voltage for all the cases were obtained; namely, input/output, inside/outside barrier and UPS loaded/unloaded. The use of different frequency spans in the FFT analyzer, allowed detailed examination of EMI/RFI levels needed for the power calculations. It also provided information throughout the entire frequency range of interest. Figures 19 and 20 illustrate the spectral content of the input current, both inside and outside the barrier, and for both UPS loaded and unloaded (frequency span 0-5kHz). Figures 19 and 20 show that the current spectrum, in addition to containing a 60-Hz component, contains harmonics of the building-power frequency. The odd harmonics are much higher than the even ones, a typical case for square waves [Ref. 10:p. 342]. The even harmonics in the current spectrum reveal that the switching waveform is not really an ideal square wave, due to finite rise and fall times. A more realistic representation of switching could be a trapezoidal wave, whose spectrum contains both even and odd components, the amplitude of odd ones being higher. Figure 21 shows that a considerable amount of EMI/RFI current also flows through the ground wire. The spectrum of the green-wire current outside and inside the barrier is shown from 0 to 5kHz.

The BFG used for the experiments was designed to provide good isolation above 20kHz, with less isolation expected below 20kHz.

UPS UNLOADED

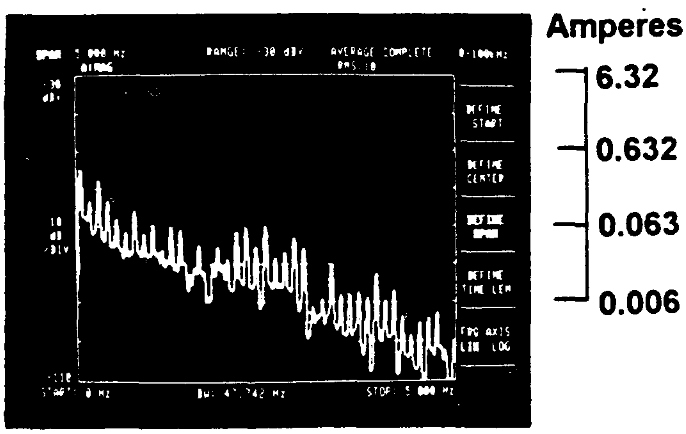


930504 1422C

60 Hz I = 0.8 A

NPS, LAB 419, UPS on,
Input, Inside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

UPS UNLOADED



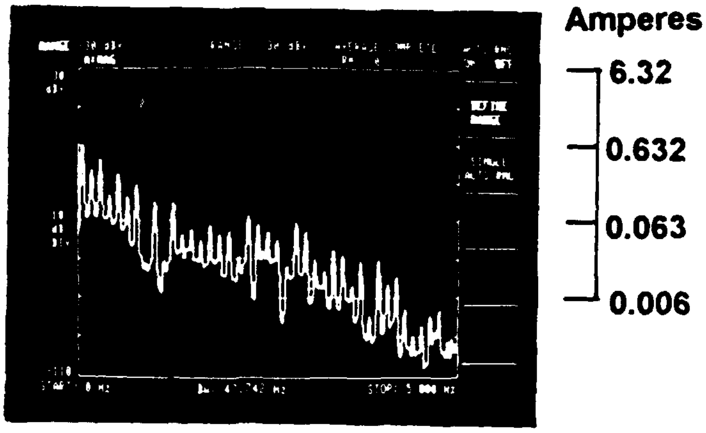
930506 1358A

60 Hz I = 0.8 mA

NPS, LAB 419, UPS on,
Input, Outside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

Figure 19. Black-Wire Current Spectrum-Input (0-5kHz)

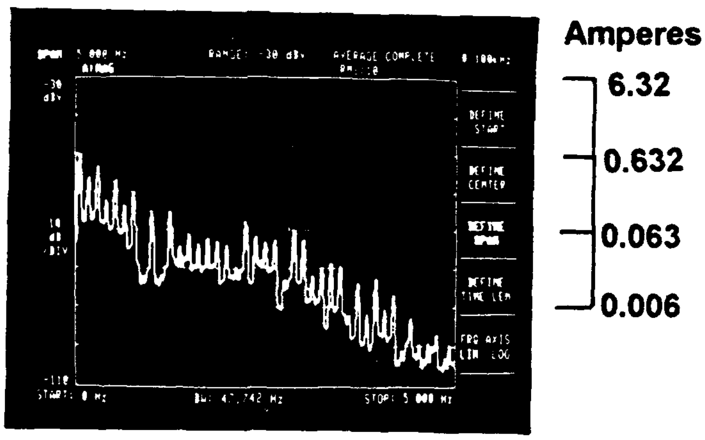
UPS LOADED



930504 1426
NPS, LAB 419, UPS on,
Input, Inside Barrier, Black Wire, Loaded
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

60 Hz I = 1.26 A

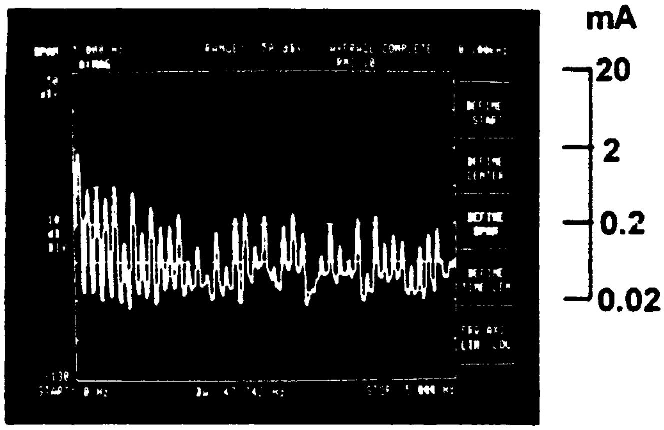
UPS LOADED



930504 1140C
NPS, LAB 419, UPS on,
Input, Outside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

60 Hz I = 1.4 A

Figure 20. Black-Wire Current Spectrum-Input-Loaded (0-5kHz)



930504 1448B
NPS, LAB 419, UPS on,
Input, Outside Barrier, Green Wire
CT4/P6021 (20/1), (10/1), +30 dB
HP3561A

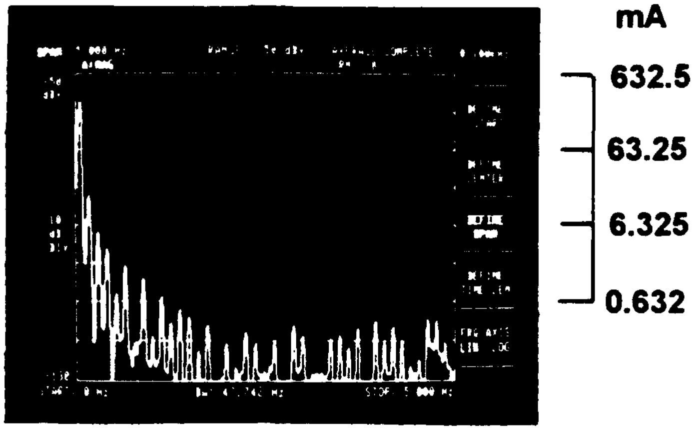
60 Hz I = 3.55 mA

Figure 21. Green-Wire Current Spectrum-Input

Figure 22 displays the spectrum of the black-wire current at the output, inside/outside the barrier. It is evident that the output current, both inside and outside the barrier, is less distorted by noise, than the input current. There are two possible explanations: either the rectification process is noisier than the DC-to-AC conversion or, the input is contaminated by conducted ambient EMI/RFI more than by UPS associated noise. Because building power was used, the origin of the noise is uncertain.

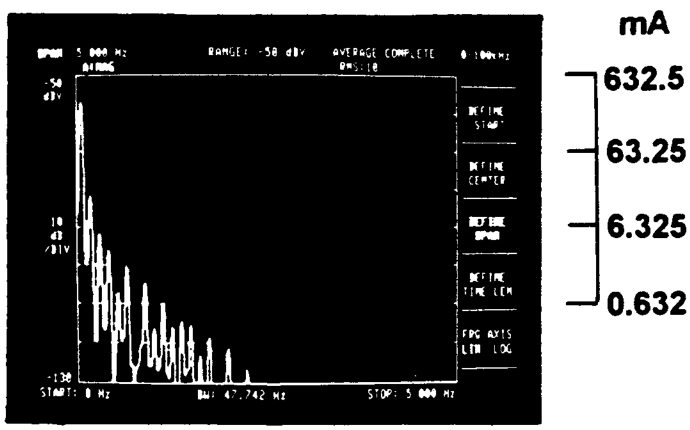
Figures 23 and 24 include spectral views of the black/green wire voltage at the input and output of the UPS. Again, the output is less "noisy" than the input.

Figures 25 and 26 show plots of the "odd harmonic power" versus frequency since most of the EMI/RFI power is distributed in the odd harmonics. The 60-Hz power is not included in the graphs because it is not EMI/RFI power. A logarithmic scale was used for the vertical axis. The solid-line curves in Figures 25 and 26 represent the case where the UPS is unloaded whereas the dashed-line curves are for the UPS-loaded case. Figures 25 and 26 show clearly that noise increases when the UPS is loaded. General conclusions will be drawn after having examined the case where the UPS is energized by a diesel generator.



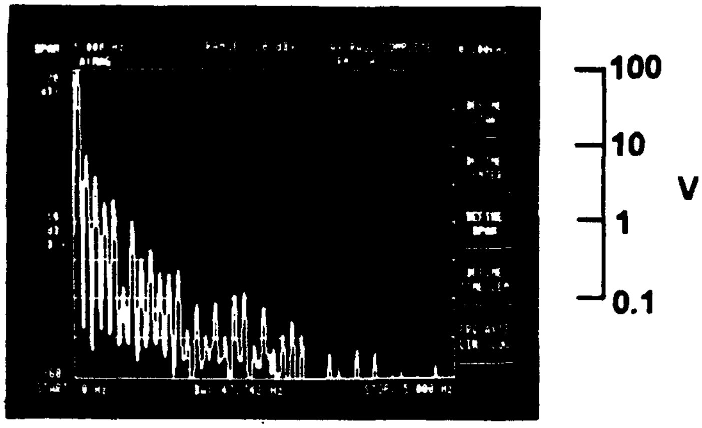
60 Hz I = 630 mA

930506 1408B
NPS, LAB 419, UPS on,
Output, Inside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

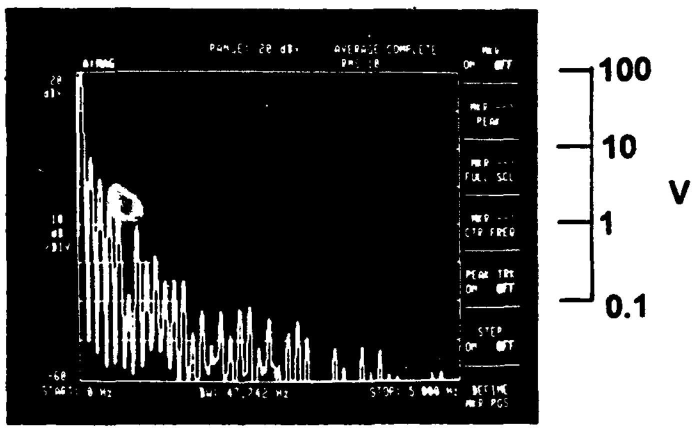


930506 1400B
NPS, LAB 419, UPS on,
Output, Outside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

Figure 22. Black-Wire Current Spectrum-Output

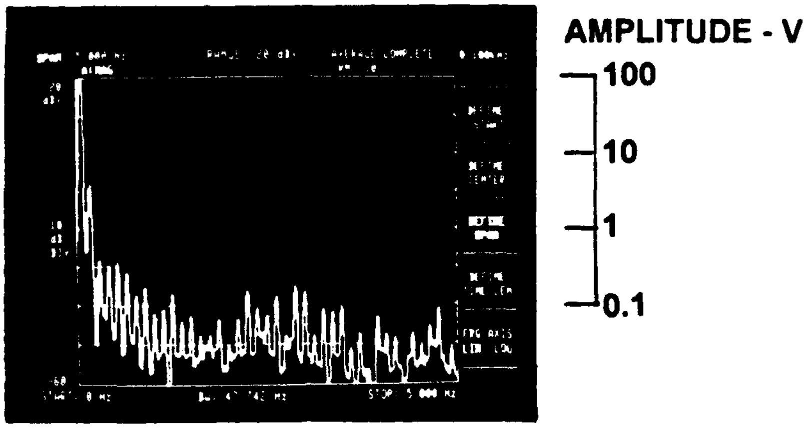


930504 1435C
NPS, LAB 419, UPS on,
Input, Inside Barrier, Black-Green Voltage
Tektronix [10:1]
HP3561A

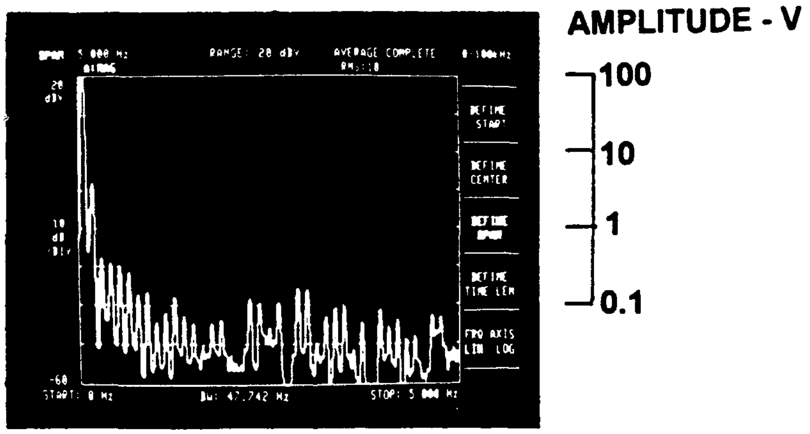


930504 1352B
NPS, LAB 419, UPS on,
Input, Outside Barrier, Black-Green Voltage
Tektronix [10:1]
HP3561A

Figure 23. Voltage Spectrum-Input



930506 1418B
NPS, LAB 419, UPS on, Output,
Inside Barrier, Black-Green Voltage
Tektronix [10:1]
HP3561A



930506 1414D
NPS, LAB 419, UPS on, Output,
Outside Barrier, Black-Green Voltage
Tektronix [10:1]
HP3561A

Figure 24. Voltage Spectrum-Output

Appendix A includes tables containing EMI/RFI power for harmonics up to 2kHz. The primary reason for choosing this part of the frequency region is that the noise power is higher at this part.

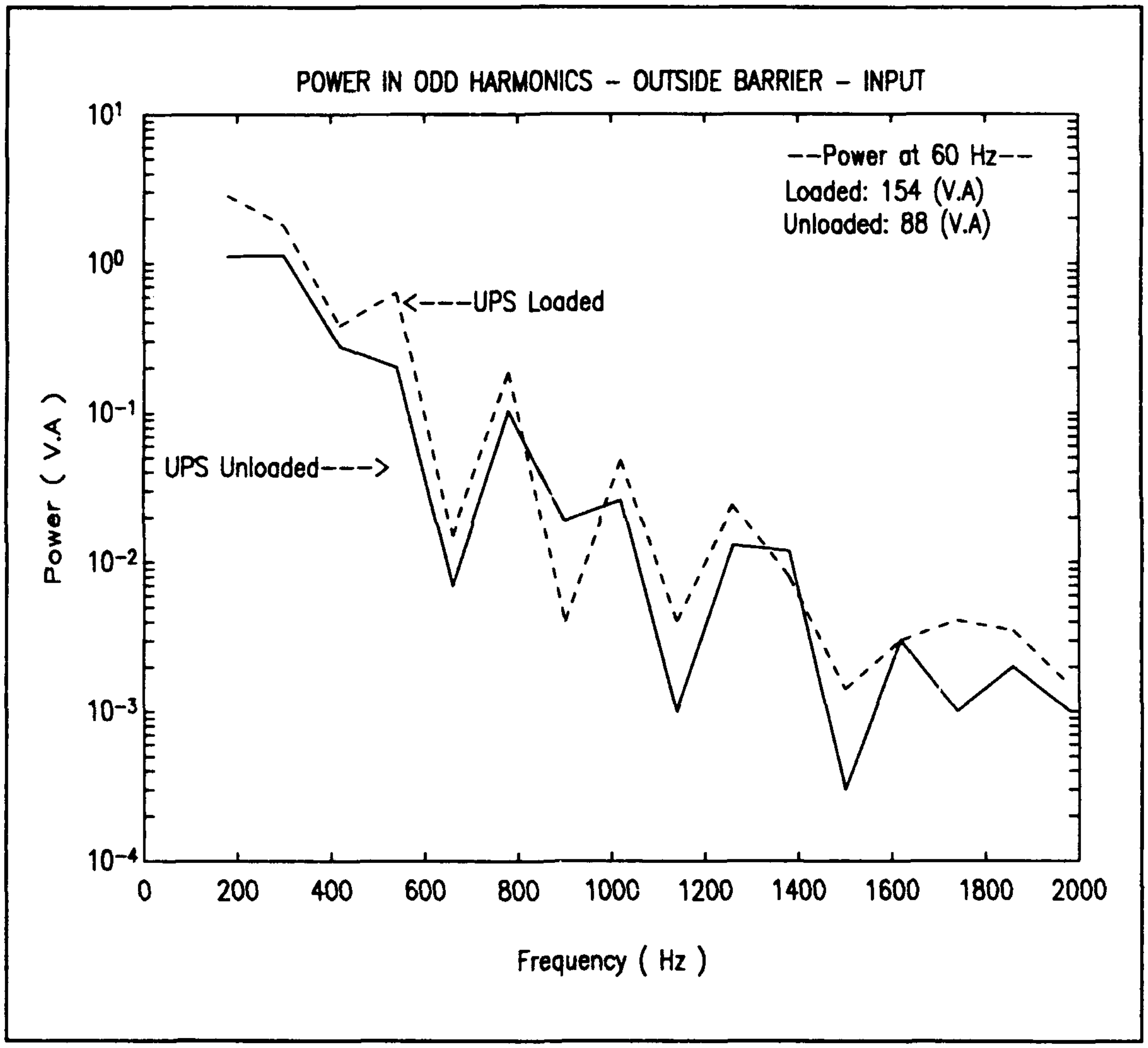


Figure 25. Harmonic Power-Outside-Input(0-2kHz)

The third round of experiments was similar to the second, the primary difference being that the power for the UPS was obtained from a diesel generator. This was done to avoid the adverse impact of noise from building power conductors on the UPS data. Spectral pictures were obtained for all cases and

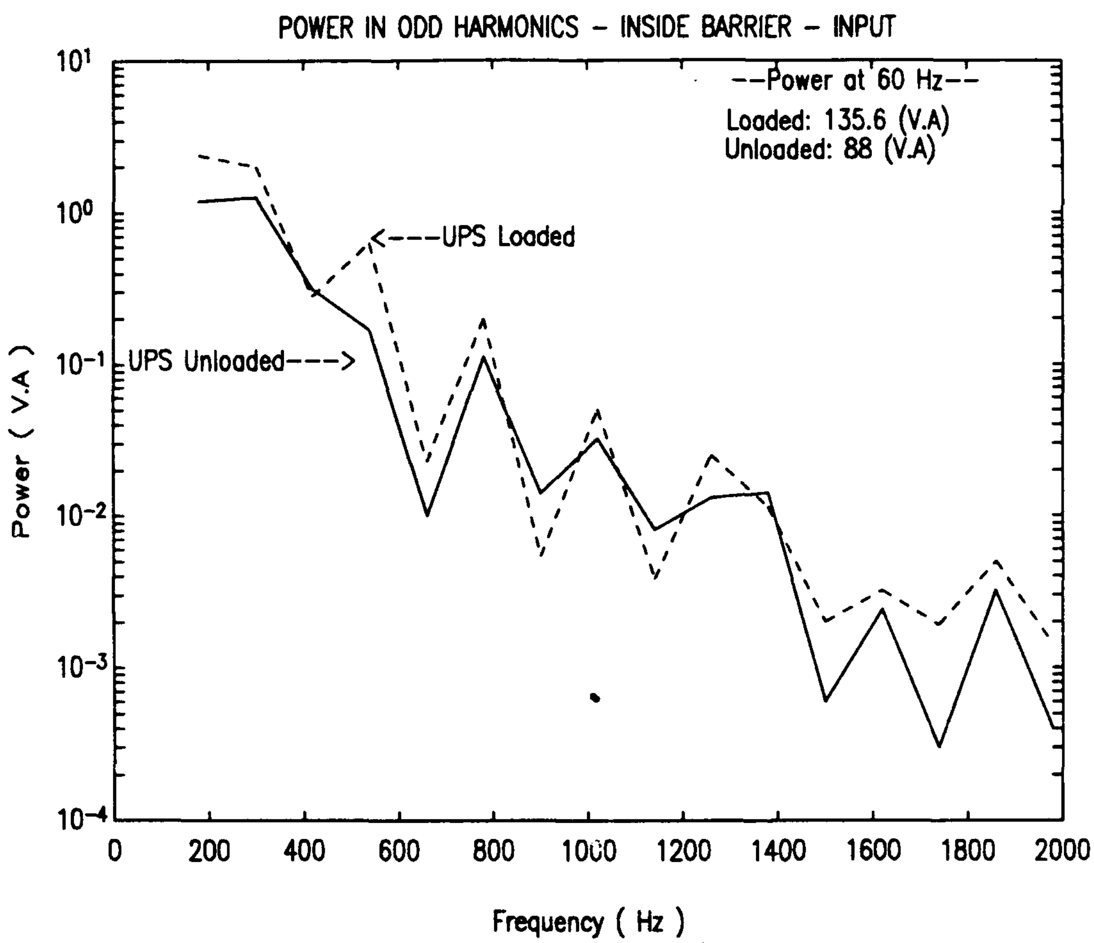
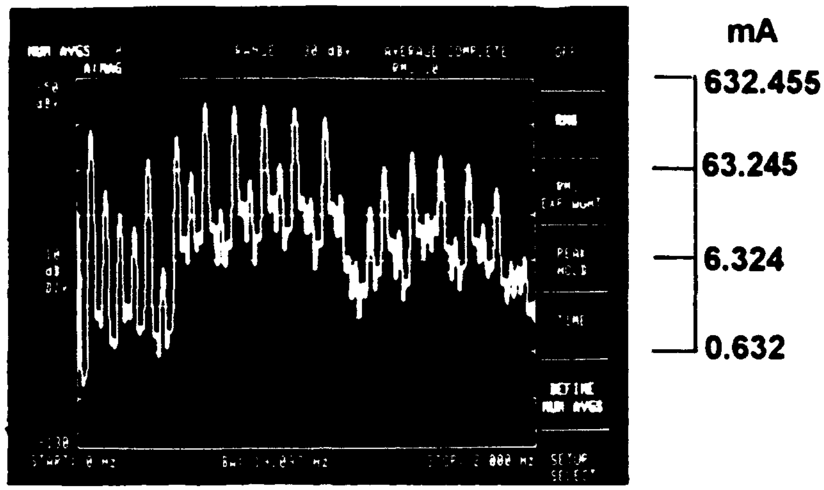


Figure 26. Harmonic Power-Inside-Input(0-2kHz)

harmonic power was also calculated for the frequency range of 0 to 2 kHz (Appendix A: Tables XIV through XXII). Measurements made to check the frequency stability of the generator's current, revealed that the line frequency was 64 Hz. This shifted all harmonics upward accordingly. The resistive load, when connected, did not appreciably change the noise level, therefore all measurements were made with the load connected to the output of the UPS.

Figures 27 and 28 show the black-wire current and voltage spectra at the input to the barrier. Figure 28 shows that the generator of 125 Volts voltage was higher than the building line voltage. Since the power-line voltage was very close to 110 Volts in the second set of measurements and nearly 125 Volts in the third set, a straightforward comparison of the results from the second and third round of experiments is not possible. Nevertheless, the third round of experiments was very important, since the power energizing the UPS was free of EMI/RFI effects and the measurements were not affected by conducted or radiated EMI/RFI originating from the source of power. Spectral pictures obtained were similar to the previous ones.

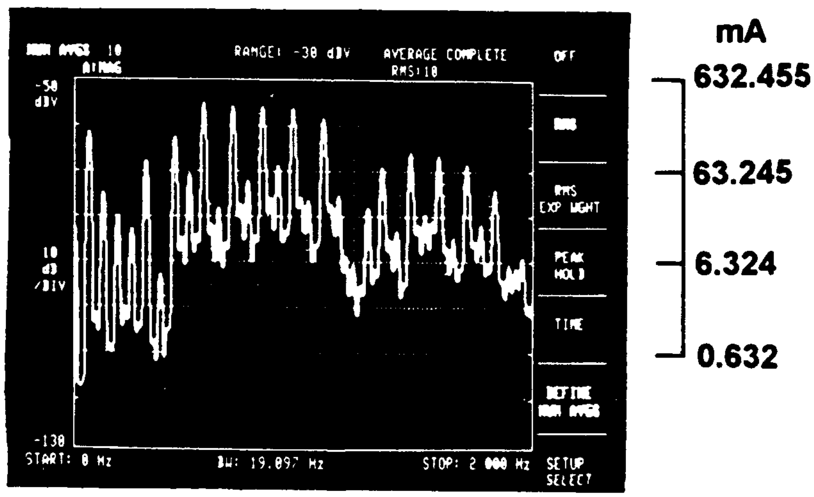
UPS LOADED



930615 1320B
NPS, Roof, UPS on,
Input, Inside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

60 Hz I = 355.66 mA

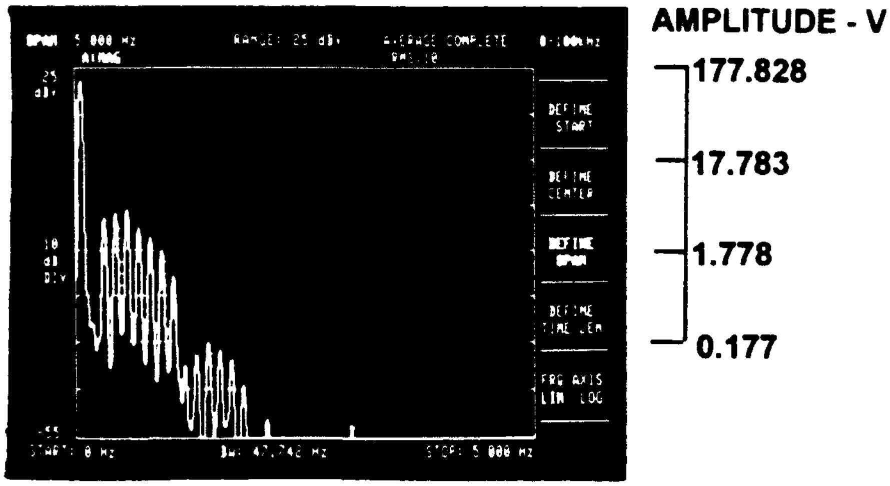
UPS LOADED



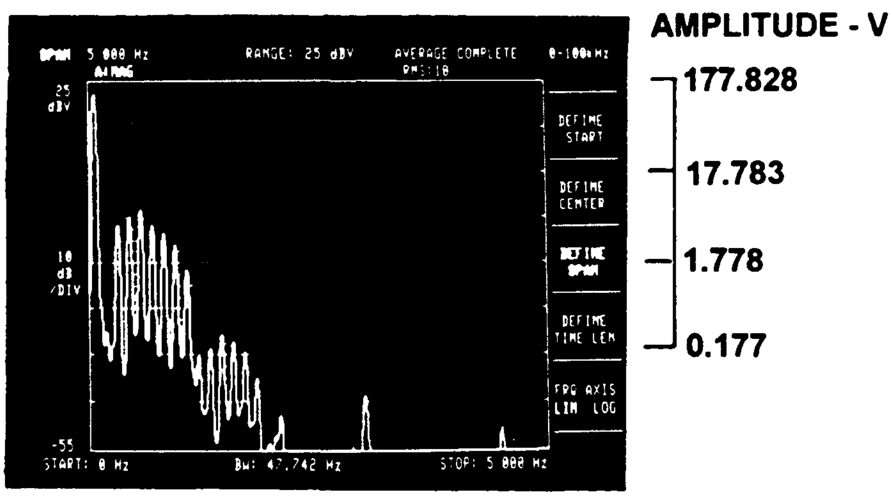
930615 1310A
NPS, Roof, Generator, UPS on,
Input, Outside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

60 Hz I = 355.66

Figure 27. Black-Wire Current Spectrum-Input-Generator



930617 1011
NPS, Roof, UPS on, Input,
Inside Barrier, Black-Green Voltage
Tektronix [10:1]
HP3561A



930617 1017C
NPS, Roof, UPS on, Input,
Outside Barrier, Black-Green Voltage
Tektronix [10:1]
HP3561A

Figure 28. Voltage Spectrum-Input-Generator

Figure 29 shows a plot of the harmonic power versus frequency, for the odd harmonics only, at the input and both inside and outside the barrier. In Figure 29 the dashed line represents the inside-the-barrier noise power, whereas the solid line represents the outside-the-barrier noise power.

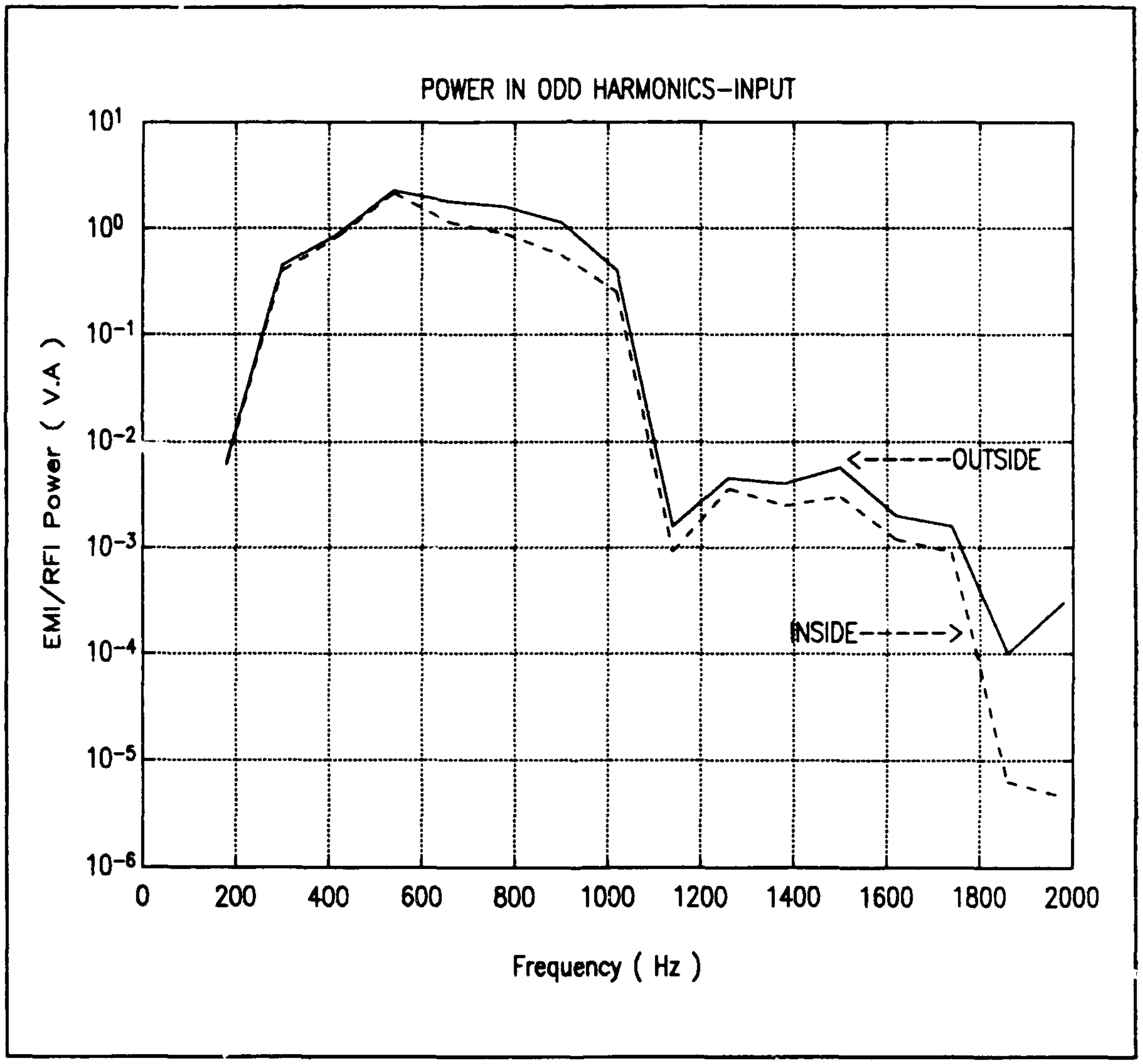


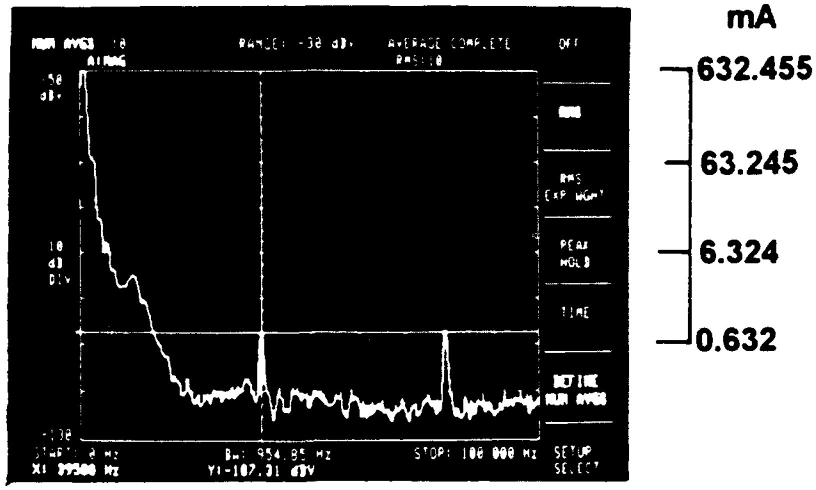
Figure 29. Harmonic Power-Input-Generator

The noise outside the barrier is slightly higher than inside, which means that a small ambient noise problem still exists.

Figures 30 and 31 show the black-wire current spectrum from 0 to 100 kHz. In all the cases illustrated in Figures 30 and 31, there is a narrowband signal at 39.5 kHz, whose amplitude is higher at the output of the UPS and inside the barrier. A harmonic of this signal is also noticed at 79 kHz. The identity of this EMI/RFI peak is not very easy to determine, since the signal and its harmonic are present everywhere. Since both the noise signal and its harmonic have a high amplitude at the output and inside the barrier, a valid explanation could be that the noise is produced by the UPS during the DC-to-AC conversion process. This noise signal is not produced by the generator, as shown by Figure 32 which proves that it also exists in the SP 415 laboratory measurements. The remaining possible explanation is that the signal is simply originating from a distant source and is picked by the power wiring and measured by the current probe.

Table I summarizes noise power results for all cases from 0 to 2 kHz. Only the case where the UPS is loaded was considered, since in real-life applications the UPS will always support a load. Table I shows that the noisiest part of the UPS is the input. A more careful look at the table reveals that the EMI/RFI power produced by the UPS from 0 to

UPS LOADED

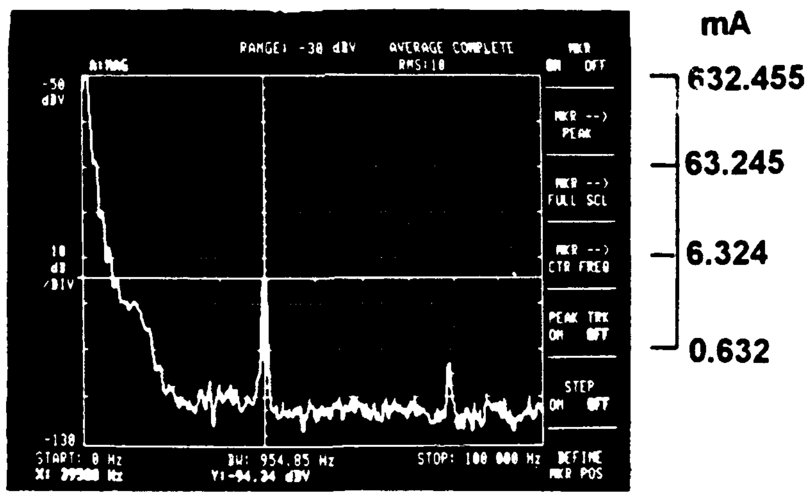


930615 1320

60 Hz I = 355.66 mA

NPS, Roof, UPS on,
Input, Inside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

UPS LOADED

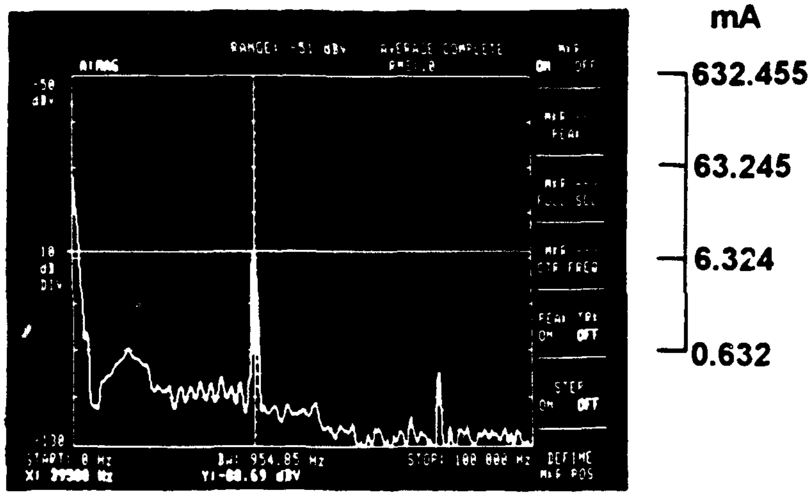


930615 1310C

60 Hz I = 355.66 mA

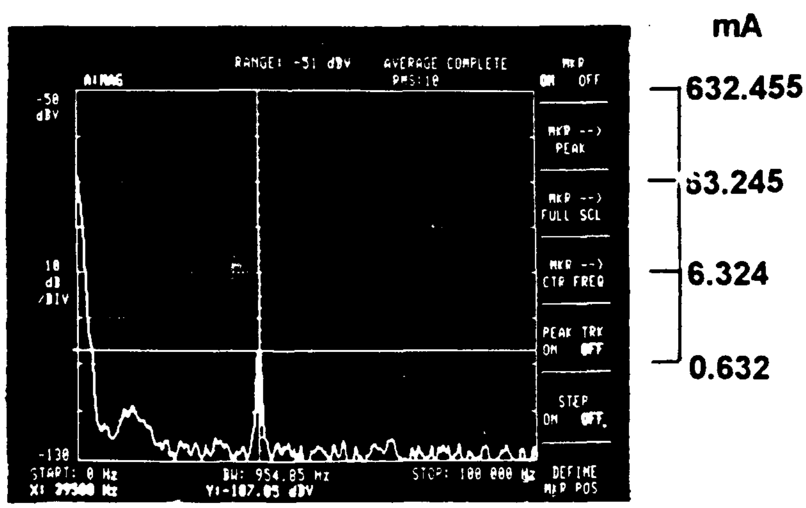
NPS, Roof, Generator, UPS on,
Input, Outside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

Figure 30. Black-Wire Current Spectrum - Input - Generator (0-100kHz)



930615 1402C
NPS, Roof, UPS on,
Output, Inside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

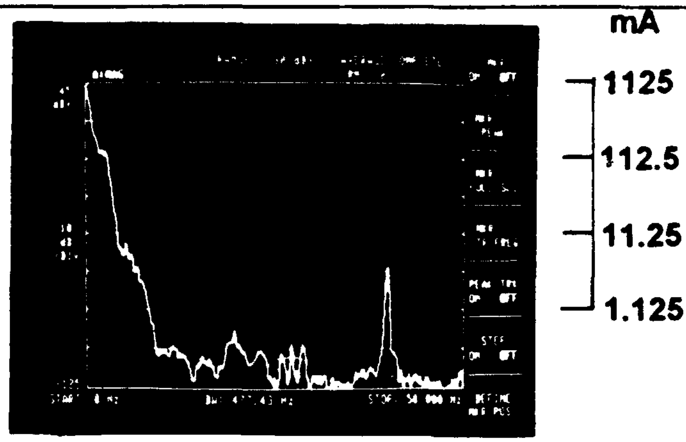
60 Hz I = 79.6 mA



930615 1415C
NPS, Roof, UPS on,
Output, Outside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

60 Hz I = 79.6 mA

Figure 31. Black-Wire Current Spectrum - Output - Generator (0-100kHz)



930429 1458
NPS, LAB 419, UPS on,
Input, Inside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

Figure 32. Black-Wire Current Spectrum-Input

Table I. HARMONIC POWER-LOAD (0-2kHz)

POSITION		POWER SOURCE	
		GENERATOR	LINE-POWER
INPUT	INSIDE	6.28 (V.A.)	5.64 (V.A.)
	OUTSIDE	8.57 (V.A.)	5.94 (V.A.)
OUTPUT	INSIDE	0.32 (V.A.)	0.086 (V.A.)
	OUTSIDE	0.45 (V.A.)	0.088 (V.A.)

2kHz is about 6 V.A. This does not represent the total noise power produced by the UPS. From 0 to 32MHz, the EMI/RFI power would be much higher, because noise generated by switching systems is broadband. A considerable amount of EMI/RFI power must be controlled by the barrier. It is questionable whether conventional filter designs can handle large amounts of EMI/RFI, especially when the power capacity of UPS is increasing substantially at modern receiving sites. The 1.2kW UPS tested is small, in terms of power, for Navy applications (receivers-data processing equipment). Larger UPS units under consideration will produce much higher levels of noise that might require the developement of new design procedures for EMI/RFI power filters.

VI. HIGH FREQUENCY EXPERIMENTS

Chapter V dealt with low-frequency EMI/RFI power estimation (0-100kHz) where good estimates of the noise power are feasible because of the availability of the proper measuring equipment. FFT Signal Analyzers with a very wide frequency span are not yet available. An approach different from the one used in Chapter Five is required for frequencies above 100kHz. This chapter is focused on broadband (100kHz-100MHz) temporal and spectral properties of EMI/RFI produced by the UPS. Laboratory results are compared to proposed maximum limits for receiving sites and an introduction to *wideband RMS* current, voltage and, power concepts is attempted.

Throughout this chapter, the term "Degree of Isolation" will be extensively used, as a measure of the effectiveness of a BFG. The degree of isolation, expressed in dB, was computed using the following equation:

$$\text{Degree of Isolation} = 20\log\left[\frac{Amplitude_{inside}}{Amplitude_{outside}}\right] \qquad (1)$$

where the amplitude of either the current or voltage is used. This definition must be used with caution since it assumes that the impedance levels are the same at the inside and outside measurement points.

The maximum EMI/RFI current limits proposed by the SNEP[2] team are:

- For large CDAA[3] receiving sites:

  2 mA for the frequency range of 0 to 10kHz

  10 μA for the frequency range of 100kHz to 50MHz

- For small sites:

  2 mA for the frequency range of 0 to 10kHz

  2 μA for the frequency range of 100kHz to 50MHz

A close look at the low-frequency spectral pictures and the tables of Appendix A, reveals that the above limits were exceeded in most of the cases.

All high-frequency measurements took place in the microwave laboratory (SP419) and spectral views of current and voltage were obtained from 0 to 100MHz. The case where the UPS was running on batteries was also examined. Figures 33 and 34 display the spectrum of black-wire current at the input and output of the barrier respectively. The photographs show that the current spectrum inside the barrier is extremely noisy. Comparing the EMI/RFI current spectra inside the barrier to those outside, a degree of isolation of more than 30dB is observed over the entire frequency range.

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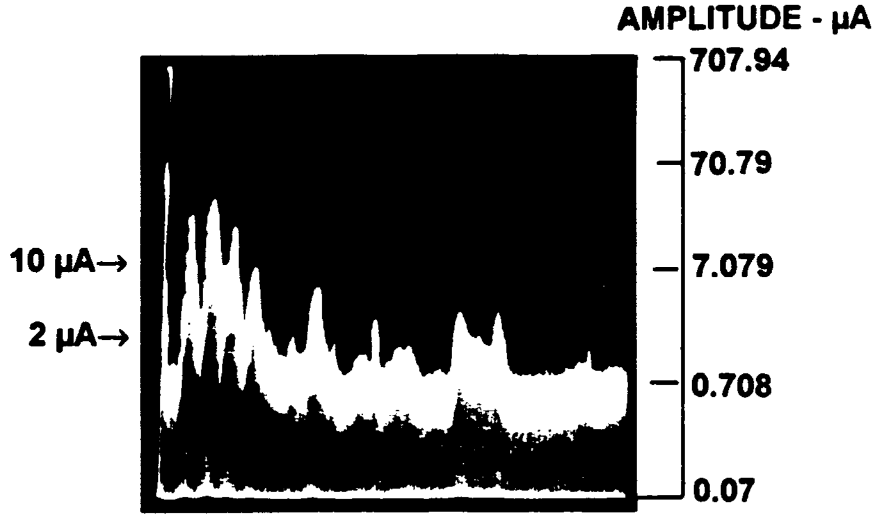
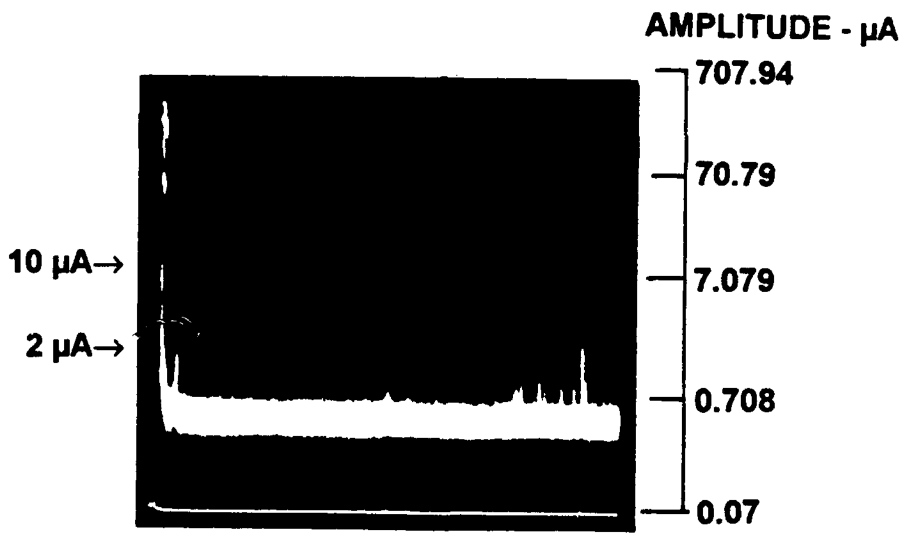
[2]Signal-to-Noise-Enhancement-Program

[3]Circularly Disposed Antenna Arrays

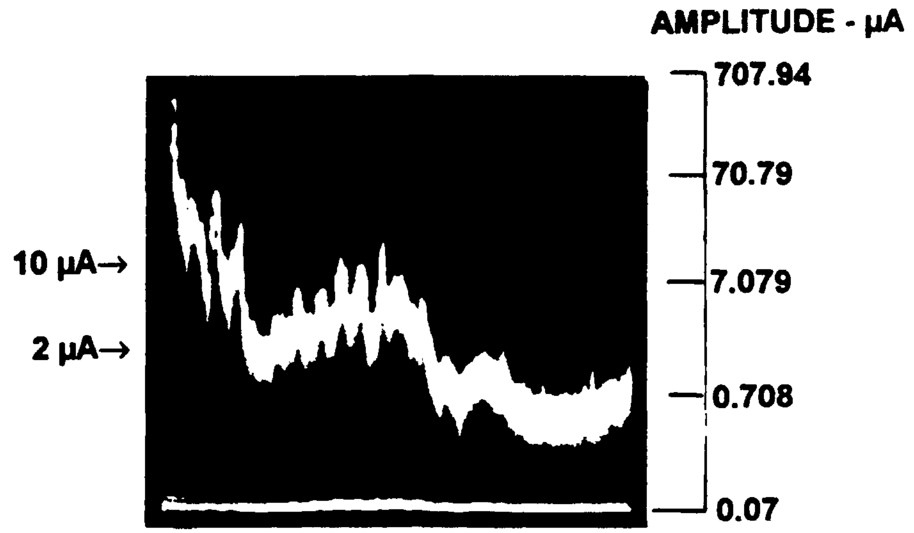


930224 2330
NPS, LAB 419, UPS Input
Inside Barrier, Black Wire/Line
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -40

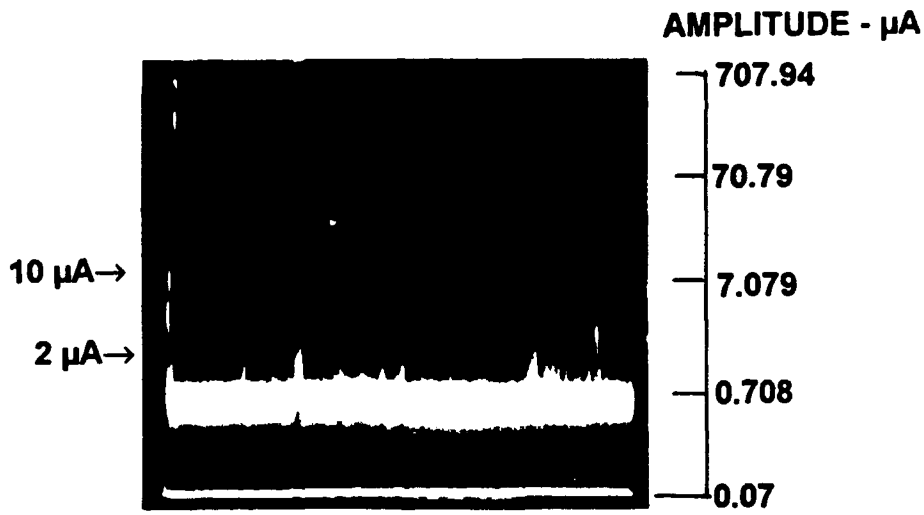


930225 1356
NPS, LAB 419, UPS Input
Outside Barrier, Black Wire/Line
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -40

Figure 33. Black-Wire Current Spectrum-Input(0-100MHz)



930224 2207
NPS, LAB 419, UPS Output
Inside Barrier, Black Wire/Line
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -40



930225 1432
NPS, LAB 419, UPS Output
Outside Barrier, Black Wire/Line
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -40

Figure 34. Black-Wire Current Spectrum-Output(0-100MHz)

Considering the $2\mu A$ and $10\mu A$ maximum EMI/RFI current limits, the current amplitude outside the barrier is less than $2\mu A$ so the BFG provides very good isolation. In the outside-the-barrier pictures, some signals are found in the upper part of the frequency region (80-100MHz). These signals probably come from local FM radio stations.

Figures 35 and 36 show the spectrum of the green-wire current at the input and the output of the barrier. Although the degree of isolation is very high at the input, some of the internally-generated noise is passed through the barrier on the UPS output conductors. This leakage of EMI/RFI is observed from 15 to 25MHz and the interference current amplitude exceeds the $2\mu A$ limit. FM radio signals are also observed in this case.

Spectral views of both current and voltage for the case where the UPS was running on batteries are found in Appendix D. Battery operation of the UPS is noisier, but even in this case, the BFG provides a satisfactory degree of isolation over a wide frequency range. There are some cases where the $2\mu A$ limit is exceeded. For example the limit is exceeded in the case of green-wire current at the output (Appendix D: Figure 48).

Thus far only the spectral characteristics of the EMI/RFI generated by the UPS have been examined. To obtain estimates for the noise power, the concept of *broadband RMS power* was

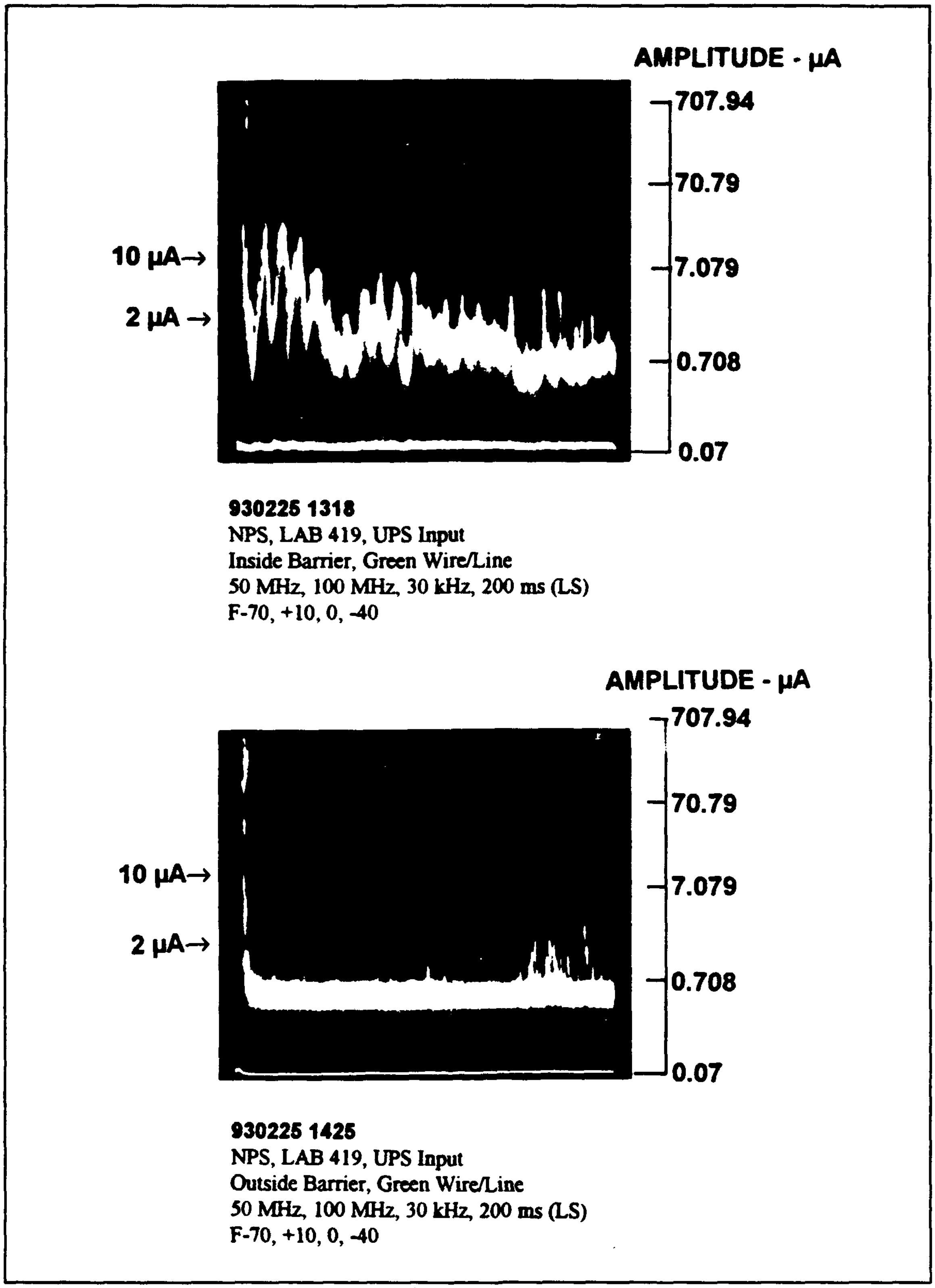
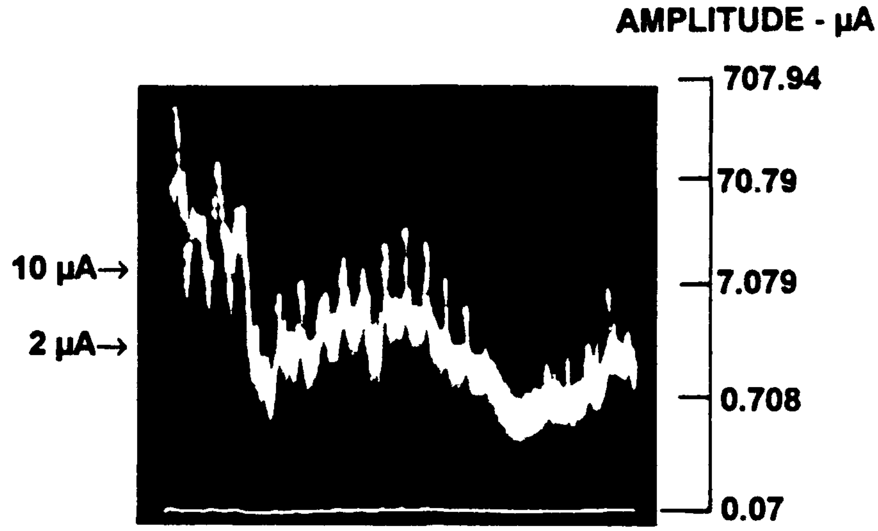
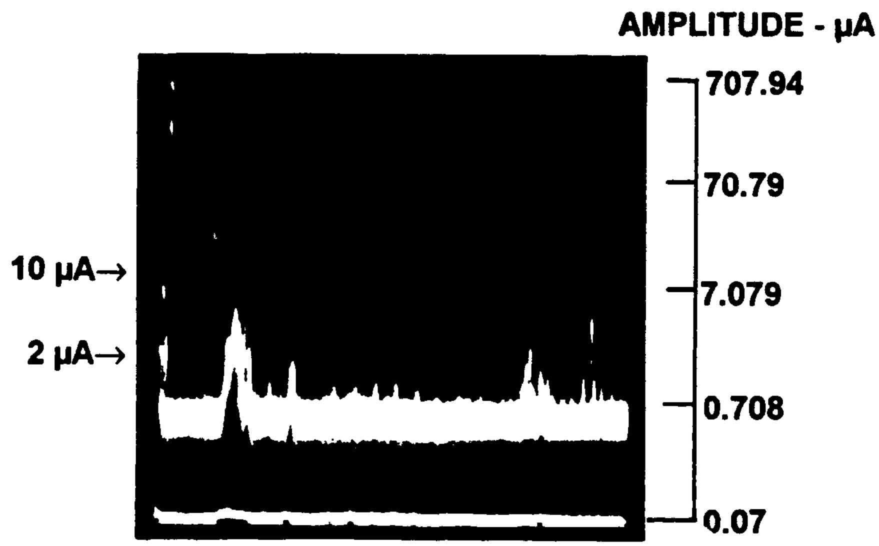


Figure 35. Current-Green Wire-Input (0-100MHz)



930225 1336
NPS, LAB 419, UPS Output
Inside Barrier, Green Wire/Line
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -40



930225 1445
NPS, LAB 419, UPS Output
Outside Barrier, Green Wire/Line
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -40

Figure 36. Current-Green Wire-Output (0-100MHz)

investigated. The objective was to obtain broadband RMS current and voltage values, and use them to derive a *broadband RMS power.* Although such a definition of power is different from the usual definition of power at a discrete frequency, it could serve as a means to compare the EMI/RFI emission levels of different devices. In other words, uninterruptible power supplies and other EMI/RFI-generating devices, could be divided into different categories according to their broadband RMS EMI/RFI power levels. Moreover, once a good estimate of the noise power in the low-frequency region is available, the RMS measurements can be taken within this frequency region and RMS power can be derived. By comparing both powers for different power UPS units, a relationship between these two could be found. That relationship could help to obtain an estimate of the noise power over wide frequency bands for various UPS sizes. In addition to the RMS power a *broadband RMS impedance* could be computed. This RMS impedance could also serve as a means for the characterization of devices such as filters of various sizes.

Unfortunately, the failure of the voltage probe did not allow obtaining values of the RMS power at the higher frequencies. Nevertheless, broadband RMS current values were obtained for different bandwidths (Appendix B). The RMS current values can be used to obtain an *RMS degree of isolation.* Using formula (1), a broadband degree of isolation based on the RMS current values can be obtained. The degree

of isolation derived from the spectral views of the current is frequency dependent, whereas an *RMS measure of isolation* would not depend on frequency. As revealed by the low-frequency experiments, the output part of the barrier is less affected by conducted ambient noise therefore, a "meaningful" *RMS degree of isolation* can be computed for the output. At the input of the barrier, the RMS isolation would be extremely low due to power-line conducted EMI/RFI. Table II disrlays the amount of isolation attained by the barrier at the output,

Table II. RMS DEGREE OF ISOLATION-OUTPUT

UPS LINE OPERATED RMS DEGREE OF ISOLATION AT THE OUTPUT			
BANDWIDTH	**100Hz-1MHz**	**2-30MHz**	**100Hz-100MHz**
BLACK WIRE	14.7dB	4.5dB	15dB
WHITE WIRE	14.1dB	10.5dB	13.8dB
GREEN WIRE	12dB	3.9dB	14.8dB

based on the RMS current measurements. From Table II the isolation, in the frequency region of 100Hz to 30MHz, is seen to be lower in the case of the green wire.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

In this study, the temporal and spectral properties of EMI/RFI generated by a 1.2kW UPS have been examined, over two frequency regions. An integrated BFG has been tested for its effectiveness in isolating noise sources from sensitive equipment. The BFG configuration provided an average current and voltage isolation of 30 to 40dB. Estimates for EMI/RFI power were obtained for the frequency region of 60Hz to 100kHz. The conclusions drawn are summarized as follows:

- There is a significant amount of EMI/RFI produced by a 1.2kW Uninterruptible Power Supply that must be controlled by the BFG. The noise power produced by the UPS under test, in some cases was as high as 1/10 of the 60-Hz output power.
- The isolation that the BFG configuration provides is low at the lower part of the frequency band of interest (below 20kHz). This fact cannot affect the received signals of interest (SOIs) but, the high-power EMI/RFI coming out of the barrier could degrade the performance of nearby sensitive equipment, especially when higher power UPS units are used.
- The current isolation that the barrier provides at the green conductor of the output of the UPS, was not sufficient to meet the tentative levels of isolation required in a receiving site.
- Ambient EMI/RFI current and voltage on the building power conductors prevented making accurate laboratory measurements of isolation provided by the BFG. It was necessary to make measurements with a clean source of power (a diesel generator).

B. RECOMMENDATIONS

After having investigated the characteristics of the EMI/RFI produced by the 1.2kW UPS, and having stated the conclusions, the following recommendations for further analysis of the subject, can be made:

- Repeat the same experiments with higher power UPS systems. The information obtained from the experiments will facilitate the design of effective BFG configurations for high-power UPS systems.
- Conventional filters might not handle the EMI/RFI power produced by a 100kW UPS. Other alternative mitigation techniques, such as large blocks of ferrite, should be investigated.
- Investigate the EMI/RFI produced by other systems that use switching, such as digital telephone switching systems and PCs, using the same approach.
- Obtain RMS current and voltage values for the above mentioned systems. Calculate the *broadband RMS power* and *broadband RMS impedance*

APPENDIX A: LOW-FREQUENCY NOISE POWER (120Hz-2kHz)

Appendix A contains tables of current and voltage values, for both the even and odd harmonics of the line-power frequency and diesel generator frequency. The noise power (V.A.) has been calculated for each harmonic. The total harmonic power (120Hz-2kHz) has also been computed. Inside/outside-barrier (IN/OUT) measurements are provided for both the input and the output of the UPS.

Table III. HARMONIC POWER-OUT/INPUT-(0-1kHz)

UPS ON & UNLOADED-BUILDING POWER MEASUREMENTS OUTSIDE THE BARRIER AT THE INPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
60	0.8	110	88
120	0.14	0.022	0.003
180	0.14	7.94	1.11
240	0.06	0.016	0.001
300	0.28	3.98	1.12
360	0.05	0.014	0.001
420	0.13	2.11	0.274
480	0.04	0.022	0.001
540	0.09	2.24	0.202
600	0.035	0.025	0.001
660	0.06	0.11	0.007
720	0.035	0.019	0.001
780	0.11	0.94	0.103
840	0.035	0.016	0.001
900	0.06	0.32	0.019
960	0.035	0.016	0.001
1020	0.065	0.4	0.026
HARMONIC POWER (120Hz-1kHz)			**2.871**

Table IV. HARMONIC POWER-OUT/INPUT-(1-2kHz)

UPS ON & UNLOADED-BUILDING POWER MEASUREMENTS OUTSIDE BARRIER AT THE INPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
1080	0.035	0.02	0.001
1140	0.04	0.2	0.001
1200	0.022	0.015	0.0003
1260	0.065	0.2	0.013
1320	0.025	0.0	0.0
1380	0.06	0.2	0.012
1440	0.025	0.0	0.0
1500	0.013	0.025	0.0003
1560	0.018	0.0	0.0
1620	0.036	0.08	0.003
1680	0.016	0.0	0.0
1740	0.01	0.07	0.001
1800	0.025	0.016	0.0004
1860	0.032	0.07	0.002
1920	0.02	0.0	0.0
1980	0.03	0.04	0.001
HARMONIC POWER (1-2kHz)			**0.035**
TOTAL HARMONIC POWER (120Hz-2kHz)			**2.906**
TOTAL POWER (60Hz-2kHz)			**90.906**

Table V. HARMONIC POWER-OUT/INPUT-LOAD-(0-1kHz)

UPS ON & LOADED-BUILDING POWER MEASUREMENTS OUTSIDE BARRIER AT THE INPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
60	1.4	110	154
120	0.178	0.022	0.004
180	0.356	7.94	2.827
240	0.134	0.016	0.002
300	0.448	3.98	1.782
360	0.119	0.014	0.002
420	0.178	2.11	0.376
480	0.089	0.022	0.002
540	0.283	2.24	0.633
600	0.07	0.025	0.002
660	0.134	0.11	0.015
720	0.045	0.019	0.001
780	0.2	0.94	0.188
840	0.032	0.016	0.001
900	0.011	0.32	0.004
960	0.022	0.016	0.001
1020	0.119	0.4	0.048
HARMONIC POWER (120Hz-1kHz)			**5.888**

Table VI. HARMONIC POWER-OUT/INPUT-LOAD-(1-2kHz)

UPS ON & LOADED-BUILDING POWER MEASUREMENTS OUTSIDE BARRIER AT THE INPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
1080	0.009	0.02	0.0002
1140	0.02	0.2	0.004
1200	0.025	0.015	0.0004
1260	0.12	0.2	0.024
1320	0.028	0.0	0.0
1380	0.04	0.2	0.008
1440	0.032	0.0	0.0
1500	0.055	0.025	0.0014
1560	0.025	0.0	0.0
1620	0.038	0.08	0.003
1680	0.02	0.0	0.0
1740	0.058	0.07	0.0041
1800	0.02	0.016	0.0003
1860	0.05	0.07	0.0035
1920	0.018	0.0	0.0
1980	0.038	0.04	0.0015
HARMONIC POWER (1-2kHz)			**0.0504**
TOTAL HARMONIC POWER (120Hz-2kHz)			**5.9384**
TOTAL POWER (60Hz-2kHz)			**159.938**

Table VII. HARMONIC POWER-IN/INPUT-(0-1kHz)

UPS ON & UNLOADED-BUILDING POWER MEASUREMENTS INSIDE BARRIER AT THE INPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
60	0.8	110	88
120	0.112	0.032	0.004
180	0.15	7.94	1.19
240	0.05	0.025	0.001
300	0.283	4.47	1.263
360	0.04	0.025	0.001
420	0.16	1.99	0.316
480	0.034	0.025	0.001
540	0.08	2.11	0.168
600	0.03	0.03	0.001
660	0.063	0.16	0.01
720	0.028	0.02	0.001
780	0.112	1.0	0.112
840	0.027	0.0	0.0
900	0.045	0.32	0.014
960	0.03	0.025	0.001
1020	0.071	0.45	0.032
HARMONIC POWER (120Hz-1kHz)			**3.115**

Table VIII. HARMONIC POWER-IN/INPUT-(1-2kHz)

UPS ON & UNLOADED-BUILDING POWER MEASUREMENTS INSIDE BARRIER AT THE INPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
1080	0.03	0.028	0.001
1140	0.034	0.224	0.008
1200	0.025	0.018	0.0005
1260	0.06	0.224	0.013
1320	0.018	0.0	0.0
1380	0.062	0.228	0.014
1440	0.02	0.005	0.0001
1500	0.015	0.04	0.0006
1560	0.02	0.005	0.0001
1620	0.03	0.08	0.0024
1680	0.014	0.004	0.0001
1740	0.009	0.03	0.0003
1800	0.002	0.028	0.0006
1860	0.032	0.1	0.0032
1920	0.018	0.018	0.0003
1980	0.016	0.027	0.0004
HARMONIC POWER (1-2kHz)			**0.0446**
TOTAL HARMONIC POWER (120Hz-2kHz)			**3.1596**
TOTAL POWER (60HZ-2kHz)			**91.1596**

Table IX. HARMONIC POWER-IN/INPUT-LOAD-(0-1kHz)

UPS ON & LOADED-BUILDING POWER MEASUREMENTS INSIDE BARRIER AT THE INPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
60	1.26	110	135.6
120	0.071	0.032	0.0023
180	0.3	7.94	2.382
240	0.065	0.025	0.0016
300	0.448	4.47	2.0026
360	0.065	0.025	0.0016
420	0.142	1.99	0.2818
480	0.06	0.025	0.0015
540	0.3	2.11	0.633
600	0.047	0.03	0.0014
660	0.144	0.16	0.023
720	0.032	0.02	0.0006
780	0.2	1.0	0.2
840	0.021	0.0	0.0
900	0.014	0.32	0.0054
960	0.017	0.025	0.0004
1020	0.112	0.45	0.0504
HARMONIC POWER (120Hz-1kHz)			**5.5876**

Table X. HARMONIC POWER-IN/INPUT-LOAD-(1-2kHz)

UPS ON & LOADED-BUILDING POWER MEASUREMENTS INSIDE BARRIER AT THE INPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
1080	0.006	0.028	0.0002
1140	0.017	0.224	0.0038
1200	0.017	0.018	0.0003
1260	0.112	0.224	0.025
1320	0.021	0.0	0.0
1380	0.05	0.228	0.0114
1440	0.023	0.005	0.0001
1500	0.05	0.04	0.002
1560	0.02	0.005	0.0001
1620	0.04	0.08	0.0032
1680	0.013	0.004	0.0001
1740	0.063	0.03	0.0019
1800	0.015	0.028	0.0004
1860	0.05	0.1	0.005
1920	0.015	0.018	0.0003
1980	0.05	0.027	0.0014
HARMONIC POWER (1-2kHz)			**0.0552**
TOTAL HARMONIC POWER (120Hz-2kHz)			**5.6428**
TOTAL POWER (60Hz-2kHz)			**141.2428**

Table XI. HARMONIC POWER-OUT/OUTPUT-(0-1kHz)

UPS ON-BUILDING POWER MEASUREMENTS OUTSIDE BARRIER AT THE OUTPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
60	0.63	110	69.3
120	0.002	0.708	0.0014
180	0.018	3.98	0.0716
240	0.0002	0.025	5.0×10^{-6}
300	0.006	0.45	0.0027
360	0.0003	0.07	2.1×10^{-5}
420	0.0036	0.316	0.011
480	0.0	0.032	0.0
540	0.001	0.32	0.0003
600	0.0002	0.02	4.0×10^{-6}
660	0.002	0.31	0.0006
720	0.0001	0.032	3.2×10^{-6}
780	0.0001	0.16	1.6×10^{-5}
840	0.0002	0.018	3.6×10^{-6}
900	0.0011	0.18	0.0002
960	0.0001	0.01	1.0×10^{-6}
1020	0.0003	0.08	2.4×10^{-5}
HARMONIC POWER (120Hz-1KHz)			**0.0879**

Table XII. HARMONIC POWER-OUT/OUTSIDE-(1-2kHz)

UPS ON-BUILDING POWER MEASUREMENTS OUTSIDE BARRIER AT THE OUTPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
1080	0.0001	0.015	1.5×10^{-6}
1140	0.0006	0.09	0.0001
1200	0.0	0.0	0.0
1260	0.0003	0.15	4.5×10^{-5}
1320	0.0	0.022	0.0
1380	0.0004	0.071	2.84×10^{-5}
1440	0.0001	0.02	2.0×10^{-6}
1500	0.0003	0.06	1.8×10^{-5}
1560	0.0	0.02	0.0
1620	0.0002	0.057	1.14×10^{-5}
1680	0.0	0.023	0.0
1740	0.0003	0.055	1.65×10^{-5}
1800	0.0	0.022	0.0
1860	0.0	0.071	0.0
1920	0.0	0.0	0.0
1980	0.0002	0.036	7.2×10^{-6}
HARMONIC POWER (1-2KHz)			**0.0002**
TOTAL HARMONIC POWER (120Hz-2KHz)			**0.0881**
TOTAL POWER (60Hz-2KHz)			**69.3881**

Table XIII. HARMONIC POWER-IN/OUTPUT-(0-1kHz)

UPS ON-BUILDING POWER MEASUREMENTS INSIDE BARRIER AT THE OUTPUT VOLTAGE AS REFERENCED TO GREEN WIRE CURRENT ON BLACK WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
60	0.63	110	69.3
120	0.002	0.708	0.0014
180	0.018	4.47	0.08
240	0.0002	0.032	6.4×10^{-6}
300	0.0063	0.4	0.0025
360	0.0003	0.08	2.4×10^{-5}
420	0.0036	0.32	0.0012
480	0.0	0.032	0.0
540	0.0006	0.32	0.0002
600	0.0003	0.025	7.5×10^{-6}
660	0.0020	0.28	0.0006
720	0.0001	0.032	3.2×10^{-6}
780	0.0002	0.15	3.0×10^{-5}
840	0.0002	0.002	4.0×10^{-7}
900	0.0013	0.18	0.0002
960	0.0001	0.002	2.0×10^{-7}
1020	0.0003	0.07	2.1×10^{-5}
HARMONIC POWER (120Hz-1kHz)			**0.0862**

Table XIV. HARMONIC POWER-IN/OUTPUT-(1-2kHz)

UPS ON-BUILDING POWER MEASUREMENTS INSIDE BARRIER AT THE OUTPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
1080	0.0001	0.022	2.2×10^{-6}
1140	0.0006	0.09	0.0001
1200	0.0	0.0	0.0
1260	0.0004	0.13	0.0001
1320	0.0	0.025	0.0
1380	0.0005	0.067	3.35×10^{-5}
1440	0.0	0.022	0.0
1500	0.0004	0.075	3.0×10^{-5}
1560	0.0	0.025	0.0
1620	0.0001	0.045	4.5×10^{-6}
1680	0.0	0.032	0.0
1740	0.0004	0.047	1.88×10^{-5}
1800	0.0	0.028	0.0
1860	0.0001	0.071	7.1×10^{-6}
1920	0.0	0.015	0.0
1980	0.0002	0.028	5.6×10^{-6}
HARMONIC POWER (1-2kHz)			**0.0003**
TOTAL HARMONIC POWER (120Hz-2kHz)			**0.0865**
TOTAL POWER (0-2kHz)			**69.3865**

Table XV. HARMONIC POWER-OUT/INPUT-GENERATOR-(0-1kHz)

UPS ON - ENERGIZED BY GENERATOR MEASUREMENTS OUTSIDE BARRIER AT THE INPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
60	0.3557	125.8925	44.7744
120	0.0283	0.5623	0.0159
180	0.02	0.3162	0.0063
240	0.015	0.1413	0.0021
300	0.0893	5.0119	0.4477
360	0.0045	0.1	0.0004
420	0.16	5.6234	0.8934
480	0.0564	0.2512	0.0142
540	0.3358	6.6834	2.244
600	0.0252	0.2239	0.0056
660	0.3557	5.0119	1.7825
720	0.0502	0.0891	0.0045
780	0.3557	4.4668	1.5887
840	0.0752	0.0282	0.0021
900	0.3557	3.1623	1.1247
960	0.0283	0.1413	0.004
1020	0.2518	1.5849	0.3991
HARMONIC POWER (120Hz-1KHz)			**8.5352**

Table XVI. HARMONIC POWER-OUT/INPUT-GENERATOR-(1-2kHz)

UPS ON - ENERGIZED BY GENERATOR MEASUREMENTS OUTSIDE BARRIER AT THE INPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
1080	0.0317	0.1	0.0032
1140	0.0089	0.1778	0.0016
1200	0.0045	0.0316	0.0001
1260	0.0252	0.1778	0.0045
1320	0.071	0.001	0.0001
1380	0.0142	0.2818	0.004
1440	0.1125	0.001	0.0001
1500	0.0224	0.2512	0.0056
1560	0.1002	0.0398	0.004
1620	0.0112	0.1778	0.002
1680	0.0893	0.0282	0.0025
1740	0.0159	0.1	0.0016
1800	0.0142	0.001	1.42×10^{-5}
1860	0.0063	0.0224	0.0001
1920	0.008	0.001	8.00×10^{-6}
1980	0.0045	0.0562	0.0003
HARMONIC POWER (1-2kHz)			**0.0297**
TOTAL HARMONIC POWER (120Hz-2kHz)			**8.5649**
TOTAL POWER (60 Hz-2kHz)			**53.3393**

Table XVII. HARMONIC POWER-IN/INPUT-GENERATOR-(0-1kHz)

UPS ON - ENERGIZED BY GENERATOR MEASUREMENTS INSIDE BARRIER AT THE INPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
60	0.3557	133.3521	47.4275
120	0.0632	0.5623	0.0356
180	0.0238	0.2512	0.006
240	0.0159	0.1995	0.0032
300	0.0893	4.4668	0.3991
360	0.0051	0.0891	0.0005
420	0.1683	5.0119	0.8434
480	0.0632	0.1778	0.0112
540	0.3991	5.3088	2.1185
600	0.0283	0.1679	0.0047
660	0.3557	3.1623	1.1247
720	0.0532	0.0447	0.0024
780	0.3557	2.5119	0.8934
840	0.071	0.0251	0.0018
900	0.317	1.7783	0.5637
960	0.0317	0.0891	0.0028
1020	0.2518	1.0	0.2518
HARMONIC POWER (120Hz-1kHz)			**6.2628**

Table XVIII. HARMONIC POWER-IN/INPUT-GENERATOR-(1-2kHz)

UPS ON -ENERGIZED BY GENERATOR MEASUREMENTS INSIDE BARRIER AT THE INPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
1080	0.0356	0.0708	0.0025
1140	0.008	0.1122	0.0009
1200	0.0036	0.001	3.60×10^{-6}
1260	0.0283	0.1259	0.0036
1320	0.071	0.001	0.0001
1380	0.0142	0.1778	0.0025
1440	0.1002	0.001	0.0001
1500	0.0224	0.1334	0.003
1560	0.0893	0.0224	0.002
1620	0.0106	0.1122	0.0012
1680	0.0752	0.001	0.0001
1740	0.0159	0.0562	0.0009
1800	0.0448	0.001	4.48×10^{-5}
1860	0.0063	0.001	6.30×10^{-6}
1920	0.008	0.001	8.00×10^{-6}
1980	0.0016	0.0282	4.51×10^{-5}
		HARMONIC POWER (1-2kHz)	**0.017**
		TOTAL HARMONIC POWER (120Hz-2kHz)	**6.2795**
		TOTAL POWER (60Hz-2kHz)	**53.7073**

Table XIX. HARMONIC POWER-IN/OUTPUT-GENERATOR-(0-1kHz)

UPS ON - ENERGIZED BY GENERATOR MEASUREMENTS INSIDE BARRIER AT THE OUTPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
60	0.0752	133.3521	10.0237
120	0.0008	0.5623	0.0004
180	0.0004	0.2661	0.0001
240	0.0004	0.1778	0.0001
300	0.008	3.7584	0.0299
360	0.0004	0.1	4.00×10^{-5}
420	0.0142	4.7315	0.067
480	0.0014	0.1679	0.0002
540	0.02	5.0119	0.1002
600	0.0014	0.1585	0.0002
660	0.0159	3.1623	0.0502
720	0.0018	0.0355	0.0001
780	0.0159	2.2387	0.0356
840	0.0025	0.0282	0.0001
900	0.0142	1.5849	0.0224
960	0.0008	0.0891	0.0001
1020	0.01	0.9441	0.0095
HARMONIC POWER (120Hz-1kHz)			**0.3161**

Table XX. HARMONIC POWER-IN/OUTPUT-GENERATOR(1-2kHz)

UPS ON - ENERGIZED BY GENERATOR MEASUREMENTS INSIDE BARRIER AT THE OUTPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
1080	0.0013	0.0708	0.0001
1140	0.0006	0.0944	0.0001
1200	0.0005	0.02	1.00×10^{-5}
1260	0.0018	0.1334	0.0002
1320	0.0005	0.0010	5.00×10^{-7}
1380	0.0032	0.1778	0.0006
1440	0.0007	0.001	7.00×10^{-7}
1500	0.0025	0.1413	0.0004
1560	0.0005	0.0251	1.25×10^{-5}
1620	0.0022	0.1259	0.0003
1680	0.0003	0.001	3.00×10^{-7}
1740	0.001	0.0631	0.0001
1800	0.0003	0.001	3.00×10^{-7}
1860	0.0002	0.001	2.00×10^{-7}
1920	0.0003	0.001	3.00×10^{-7}
1980	0.0006	0.001	6.00×10^{-7}
HARMONIC POWER (1-2kHz)			**0.0018**
TOTAL HARMONIC POWER (120Hz-2kHz)			**0.3179**
TOTAL POWER (60Hz-2kHz)			**10.3416**

Table XXI. HARMONIC POWER-OUT/OUTPUT-GENERATOR-(0-1kHz)

UPS ON - ENERGIZED BY GENERATOR MEASUREMENTS OUTSIDE BARRIER AT THE OUTPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
60	0.0893	133.3521	11.9132
120	0.0009	0.631	0.0006
180	0.0004	0.3162	0.0001
240	0.0004	0.2239	0.0001
300	0.008	4.7315	0.0377
360	0.0004	0.0944	3.78×10^{-5}
420	0.0126	5.6234	0.071
480	0.0016	0.2818	0.0004
540	0.02	7.0795	0.1416
600	0.0016	0.7499	0.0012
660	0.0159	4.7315	0.0752
720	0.002	0.1	0.0002
780	0.0159	3.9811	0.0632
840	0.0028	0.0224	0.0001
900	0.0142	2.8184	0.0399
960	0.001	0.1259	0.0001
1020	0.01	1.6788	0.0168
HARMONIC POWER (120Hz-1kHz)			**0.4482**

Table XXII. HARMONIC POWER-OUT/OUTPUT-GENERATOR-(1-2kHz)

UPS ON - ENERGIZED BY GENERATOR MEASUREMENTS OUTSIDE BARRIER AT THE OUTPUT CURRENT ON BLACK WIRE VOLTAGE AS REFERENCED TO GREEN WIRE			
FREQUENCY (Hz)	**CURRENT (A)**	**VOLTAGE (V)**	**POWER (V.A.)**
1080	0.0022	0.1189	0.0001
1140	0.0006	0.1778	0.0001
1200	0.0005	0.0355	1.77×10^{-5}
1260	0.002	0.2512	0.0002
1320	0.0004	0.0224	8.96×10^{-6}
1380	0.001	0.3548	0.0006
1440	0.0007	0.001	7.00×10^{-7}
1500	0.0025	0.2512	0.0004
1560	0.0004	0.0473	1.89×10^{-5}
1620	0.002	0.2239	0.0003
1680	0.0003	0.0282	8.46×10^{-6}
1740	0.001	0.1122	0.0001
1800	0.0002	0.001	2.00×10^{-7}
1860	0.0002	0.0251	5.02×10^{-6}
1920	0.0003	0.0355	1.06×10^{-5}
1980	0.0005	0.0501	2.50×10^{-5}
HARMONIC POWER (1-2kHz)			**0.0019**
TOTAL HARMONIC POWER (120Hz-2kHz)			**0.4501**
TOTAL POWER (60Hz-2kHz)			**12.3633**

APPENDIX B: BROADBAND RMS CURRENT VALUES

Appendix B contains broadband RMS current measurements. Measurements were taken with the Boonton RMS meter. All cases were considered, namely: UPS on; UPS running on batteries; inside/outside barrier; input/output.

Table XXIII. RMS CURRENT-INSIDE-INPUT

UPS INSIDE BARRIER - LINE OPERATED MEASUREMENTS INSIDE BARRIER AT THE INPUT BROADBAND RMS CURRENTS			
BANDWIDTH	**100Hz-1MHz**	**2-30MHz**	**100Hz-100MHz**
BLACK WIRE CURRENT (mA)	8.5	0.46	8.2
WHITE WIRE CURRENT (mA)	8.6	0.44	8.15
GREEN WIRE CURRENT (mA)	0.55	0.49	0.53

Table XXIV. RMS CURRENT-OUTSIDE-INPUT

UPS INSIDE BARRIER - LINE OPERATED MEASUREMENTS OUTSIDE BARRIER AT THE INPUT BROADBAND RMS CURRENTS			
BANDWIDTH	**100Hz-1MHz**	**2-30MHz**	**100Hz-100MHz**
BLACK WIRE CURRENT (mA)	11.19	0.36	11.78
WHITE WIRE CURRENT (mA)	11.5	0.34	11.5
GREEN WIRE CURRENT (mA)	1.35	0.34	1.71

Table XXV. RMS CURRENT-INSIDE-OUTPUT

UPS INSIDE BARRIER - LINE OPERATED MEASUREMENTS INSIDE BARRIER AT THE OUTPUT BROADBAND RMS CURRENTS			
BANDWIDTH	**100Hz-1MHz**	**2-30MHz**	**100Hz-100MHz**
BLACK WIRE CURRENT (mA)	4.61	0.64	4.87
WHITE WIRE CURRENT (mA)	4.1	1.18	4.25
GREEN WIRE CURRENT (mA)	1.39	0.55	2.04

Table XXVI. RMS CURRENT-OUTSIDE-OUTPUT

UPS INSIDE BARRIER - LINE OPERATED MEASUREMENTS OUTSIDE BARRIER AT THE OUTPUT BROADBAND RMS CURRENTS			
BANDWIDTH	**100Hz-1MHz**	**2-30MHz**	**100Hz-100MHz**
BLACK WIRE CURRENT (mA)	0.85	0.38	0.87
WHITE WIRE CURRENT (mA)	0.81	0.35	0.87
GREEN WIRE CURRENT (mA)	0.35	0.35	0.37

Table XXVII. RMS CURRENT-OUTSIDE-OUTPUT(BATTERY)

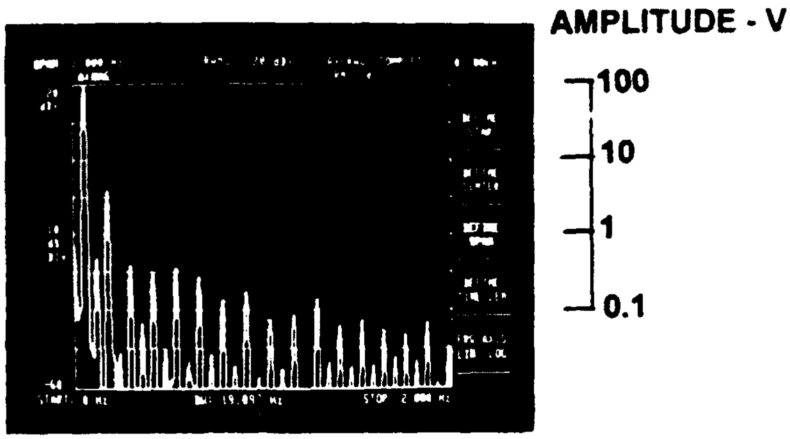
UPS INSIDE BARRIER - RUNNING ON BATTERIES MEASUREMENTS OUTSIDE BARRIER AT THE OUTPUT BROADBAND RMS CURRENTS			
BANDWIDTH	**100Hz-1MHz**	**2-30MHz**	**100Hz-100MHz**
BLACK WIRE CURRENT (mA)	0.84	0.34	0.87
WHITE WIRE CURRENT (mA)	0.84	0.32	0.86
GREEN WIRE CURRENT (mA)	0.32	0.32	0.34

Table XXVIII. RMS CURRENT-INSIDE-OUTPUT(BATTERY)

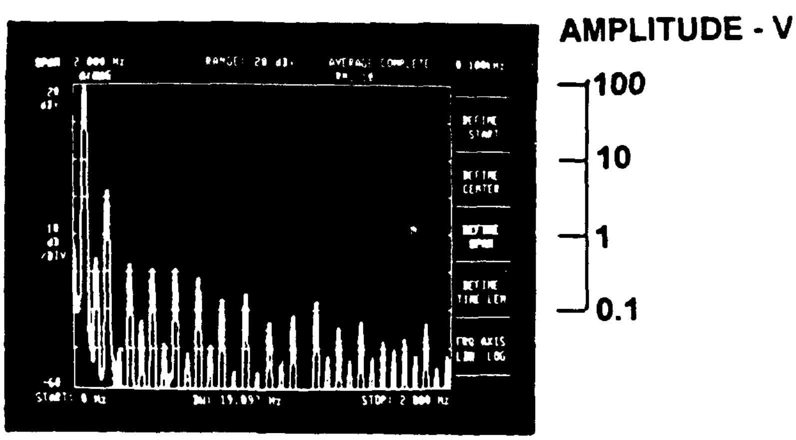
UPS INSIDE BARRIER - RUNNING ON BATTERIES MEASUREMENTS INSIDE BARRIER AT THE OUTPUT BROADBAND RMS CURRENTS			
BANDWIDTH	**100Hz-1MHz**	**2-30MHz**	**100Hz-100MHz**
BLACK WIRE CURRENT (mA)	3.95	0.42	4.14
WHITE WIRE CURRENT (mA)	3.74	0.52	4.05
GREEN WIRE CURRENT (mA)	1.52	0.46	1.77

APPENDIX C: LOW-FREQUENCY CURRENT AND VOLTAGE SPECTRA

Appendix C contains all current and voltage spectral views used to produce Tables III through XXII. Some pictures considered important for the study of low-frequency EMI/RFI characteristics of a UPS, are also included.

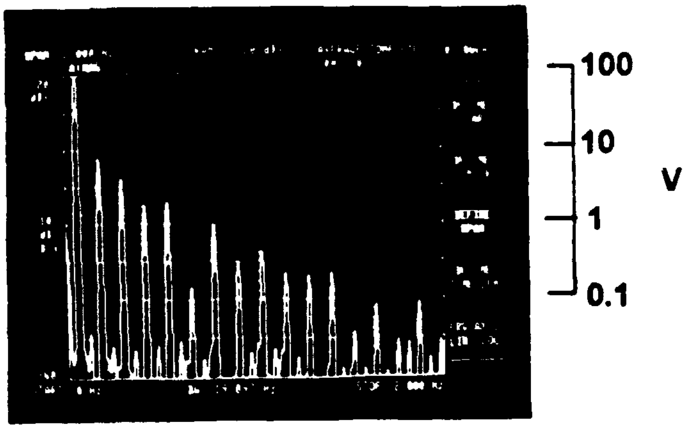


930506 1414B
NPS, LAB 419, UPS on, Output,
Outside Barrier, Black-Green Voltage
Tektronix [10:1] Voltage Probe
HP3561A

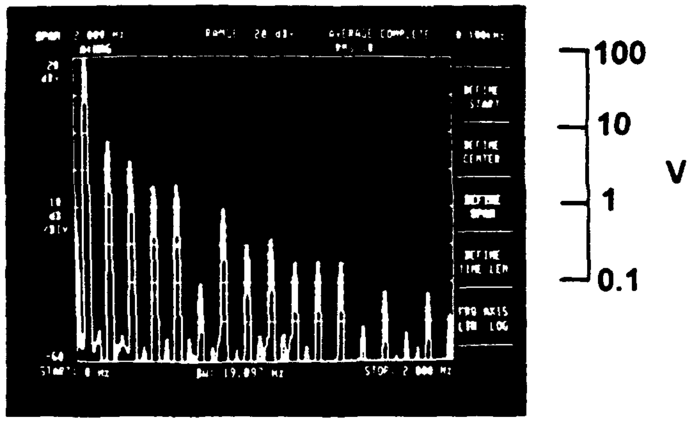


930506 1418A
NPS, LAB 419, UPS on, Output,
Inside Barrier, Black-Green Voltage
Tektronix [10:1] Voltage Probe
HP3561A

Figure 37. Voltage Spectrum-Output

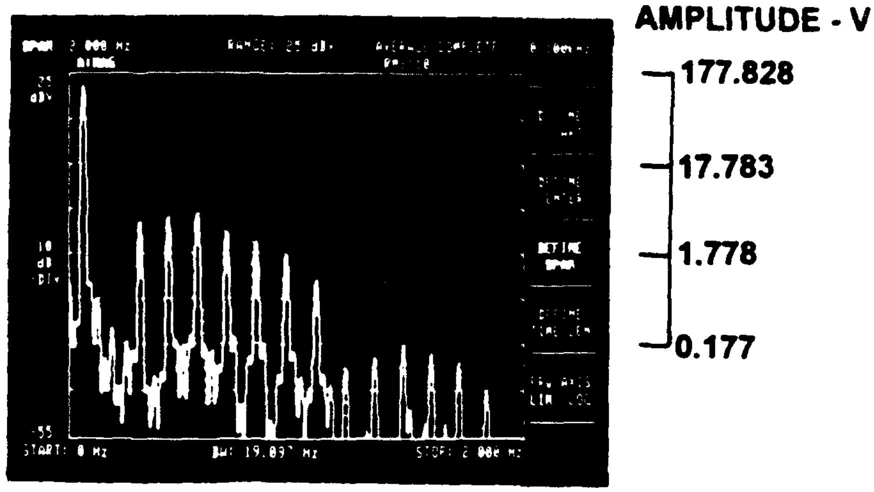


930504 1435A
NPS, LAB 419, UPS on,
Input, Inside Barrier, Black-Green Voltage
Tektronix [10:1] Voltage Probe
HP3561A

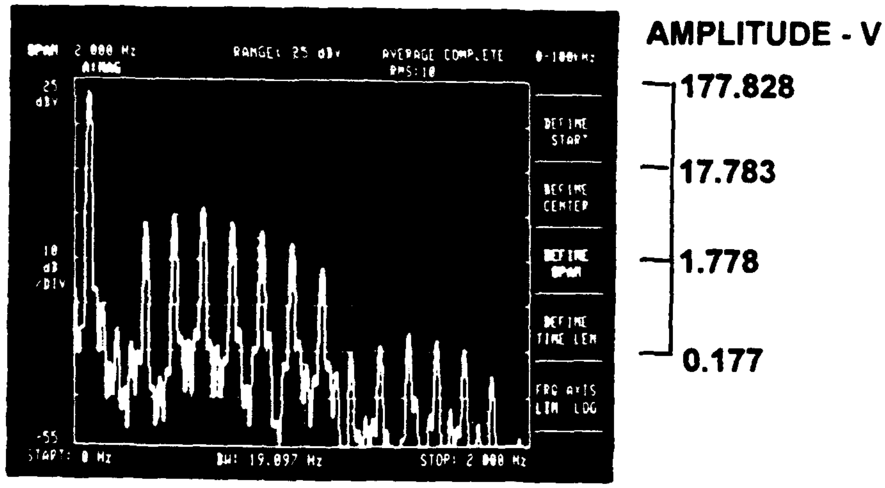


930504 1352C
NPS, LAB 419, UPS on,
Input, Outside Barrier, Black-Green Voltage
Tektronix [10:1] Voltage Probe
HP3561A

Figure 38. Voltage Spectrum-Input

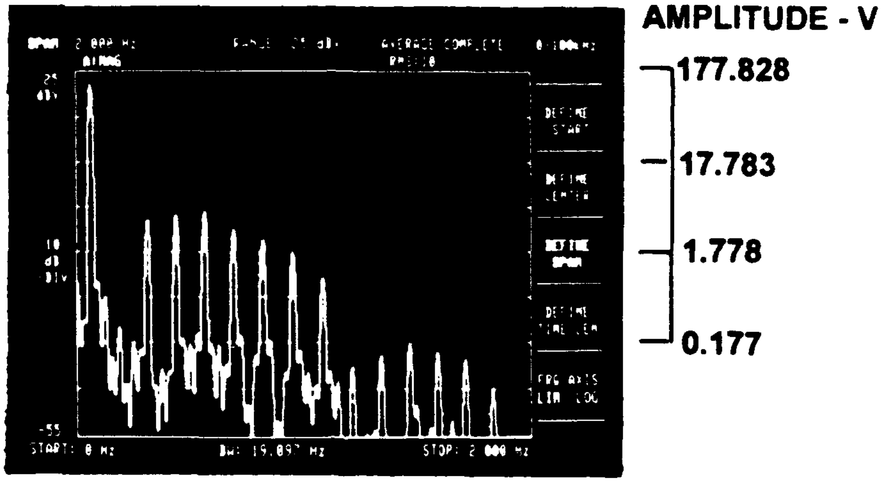


930617 1011A
NPS, Roof, UPS on, Input,
Inside Barrier, Black-Green Voltage
Tektronix [10:1] Voltage Probe
HP3561A

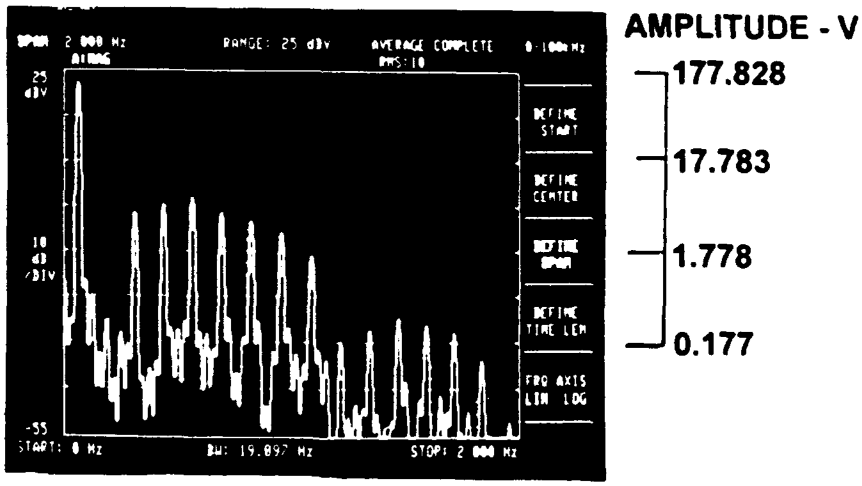


930617 1017B
NPS, Roof, UPS on, Input,
Outside Barrier, Black-Green Voltage
Tektronix [10:1] Voltage Probe
HP3561A

Figure 39. Voltage Spectrum-Input-Generator

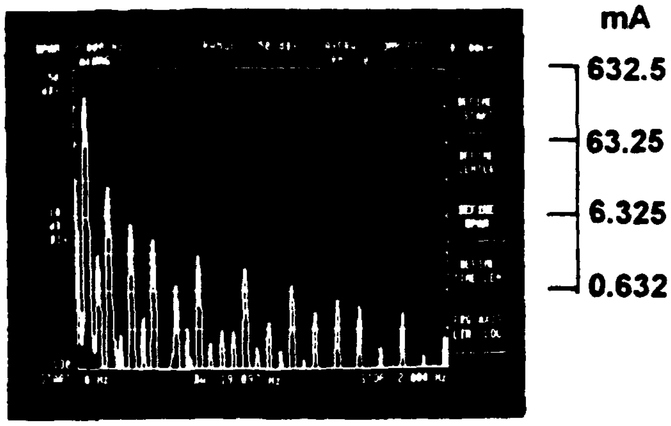


930617 1003B
NPS, Roof, UPS on, Output,
Inside Barrier, Black-Green Voltage
Tektronix [10:1] Voltage Probe
HP3561A



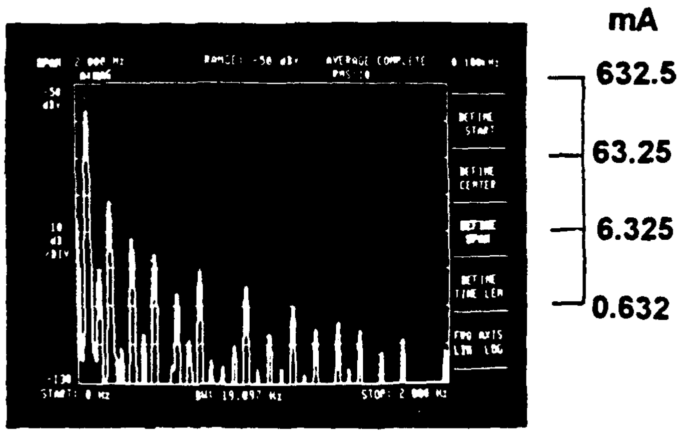
930617 1022A
NPS, Roof, UPS on, Output,
Outside Barrier, Black-Green Voltage
Tektronix [10:1] Voltage Probe
HP3561A

Figure 40. Voltage Spectrum-Output-Generator



60 Hz I = 630 mA

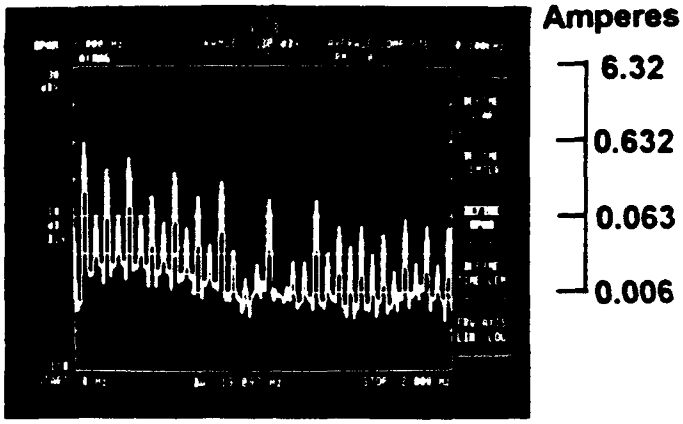
930506 1408A
NPS, LAB 419, UPS on,
Output, Inside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A



930506 1400A
NPS, LAB 419, UPS on,
Output, Outside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

Figure 41. Current-Black Wire-Output

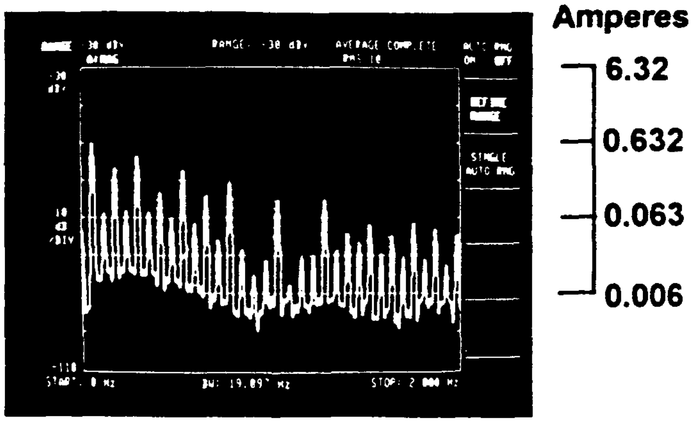
UPS LOADED



60 Hz I = 1.26A

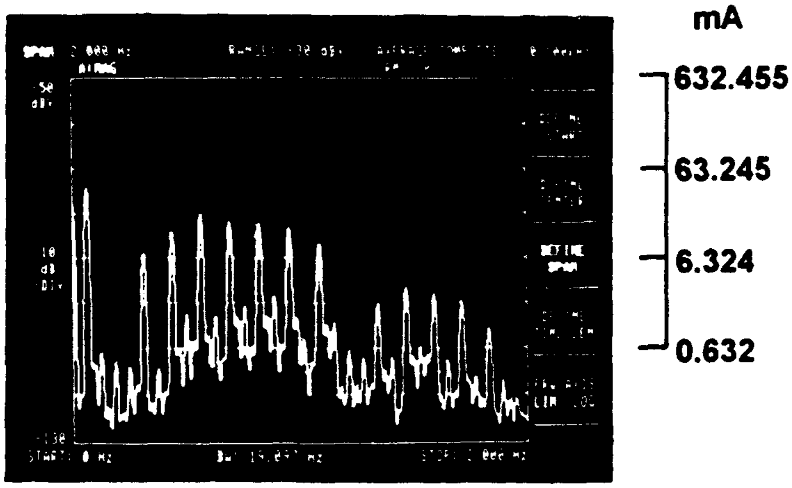
930504 1426A
NPS, LAB 419, UPS on,
Input, Inside Barrier, Black Wire, Loaded
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

UPS LOADED



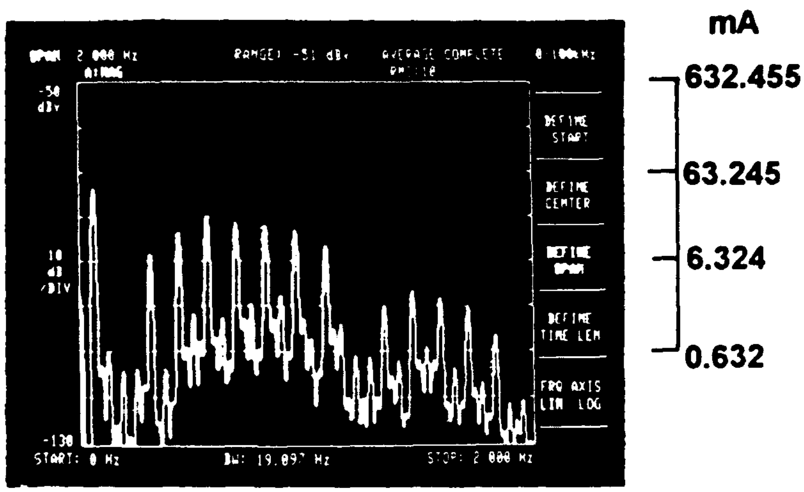
930504 1140B
NPS, LAB 419, UPS on,
Input, Outside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

Figure 42. Current-Black Wire-Input



60 Hz I = 79.6 mA

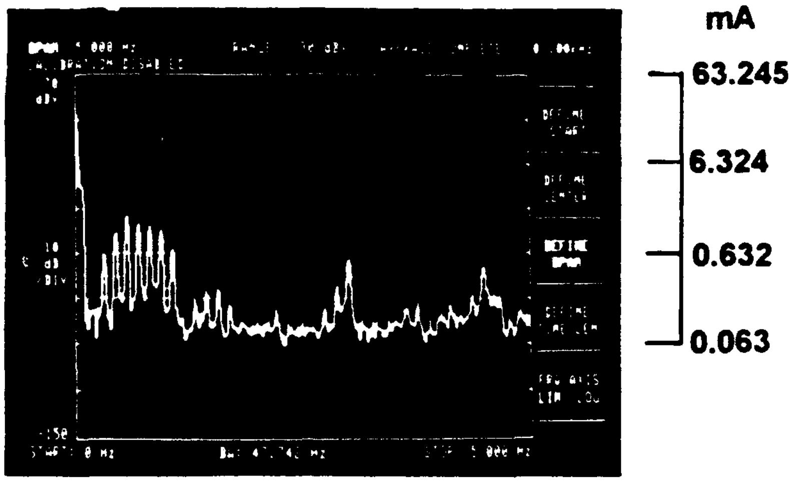
930615 1402A
NPS, Roof, UPS on,
Output, Inside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A



60 Hz I = 79.6 mA

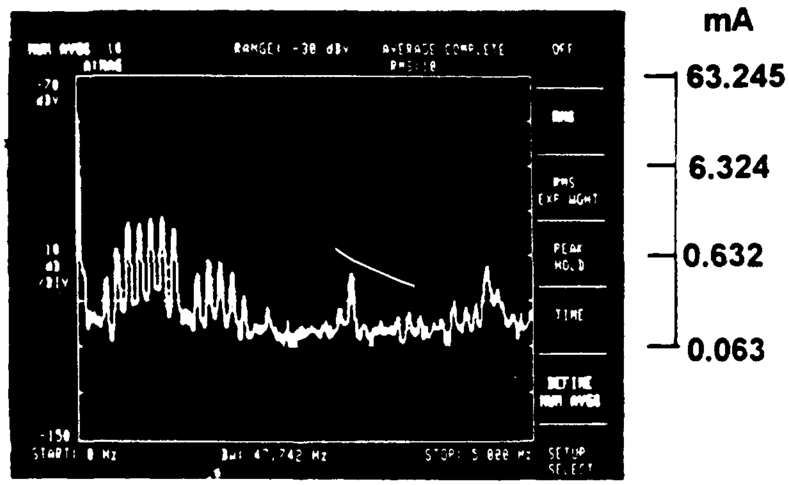
930615 1415A
NPS, Roof, UPS on,
Output, Outside Barrier, Black Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

Figure 43. Current-Black Wire-Output-Generator



930615 1330B
NPS, Roof, UPS on,
Input, Inside Barrier, Green Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

60 Hz I = 7.1 mA



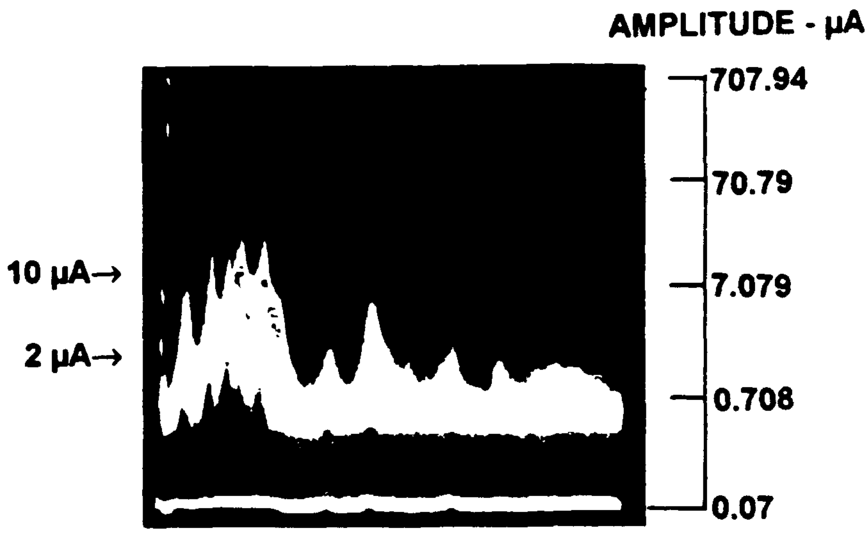
930615 1340B
NPS, Roof, UPS on,
Input, Outside Barrier, Green Wire
CT4/P6021 (20/1), (10/1), 0 dB
HP3561A

60 Hz I = 0.9 mA

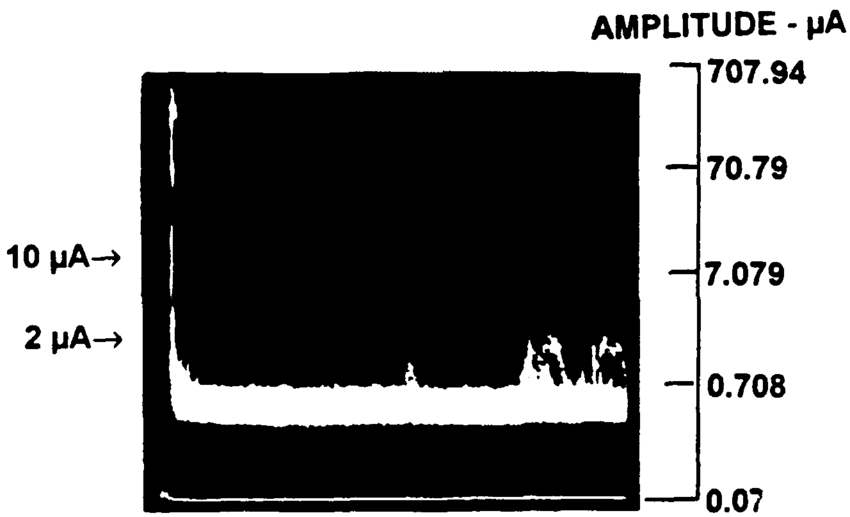
Figure 44. Current-Green Wire-Input-Generator

APPENDIX D: HIGH-FREQUENCY CURRENT AND VOLTAGE SPECTRA

Appendix D contains current and voltage spectral views from 0 to 100MHz and for the case when the UPS was running on batteries. Furthermore, pictures considered important for the documentation of the broadband EMI/RFI properties of the UPS under test, are included.

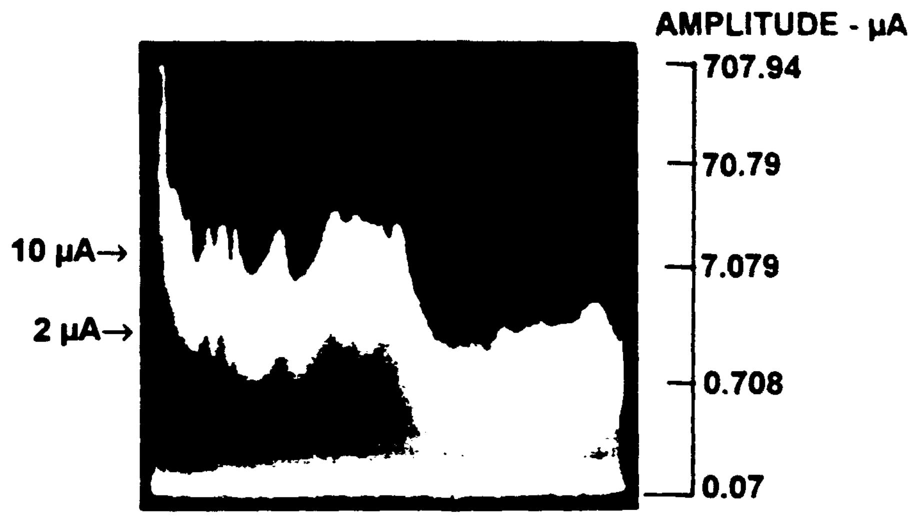


930225 1916
NPS, LAB 419, UPS Input
Inside Barrier, Black Wire/Battery
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -40

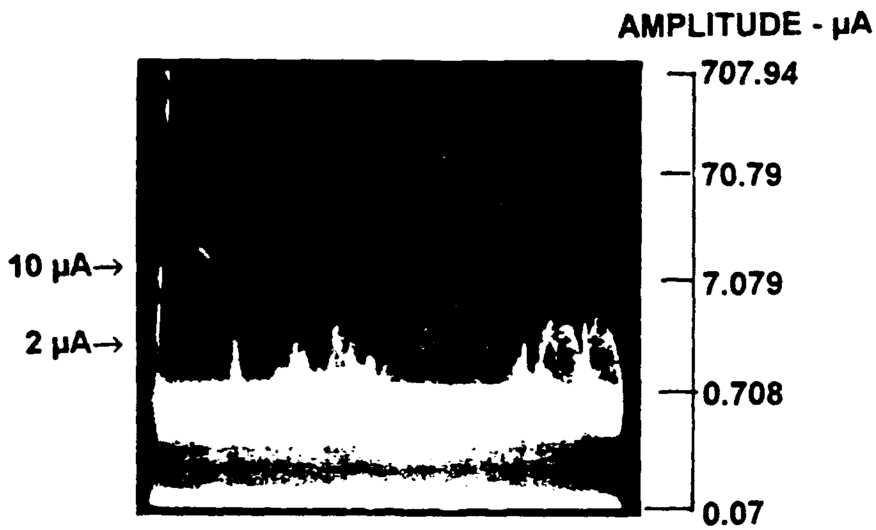


930225 2022
NPS, LAB 419, UPS Input
Outside Barrier, Black Wire/Battery
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -40

Figure 45. Current-Black Wire-Input-Battery Operated

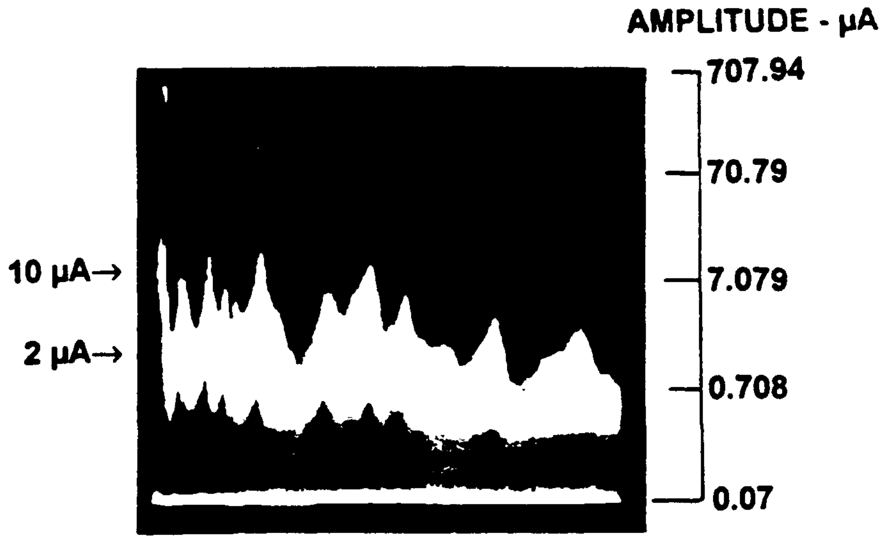


930225 1930
NPS, LAB 419, UPS Output
Inside Barrier, Black Wire/Battery
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -40

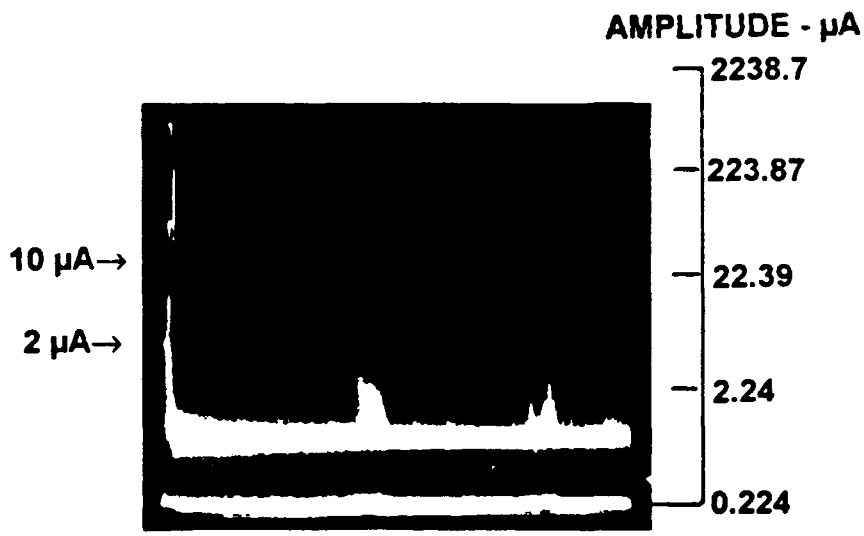


930225 2000
NPS, LAB 419, UPS Output
Outside Barrier, Black Wire/Battery
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -40

Figure 46. Current-Black Wire-Output-Battery Operated

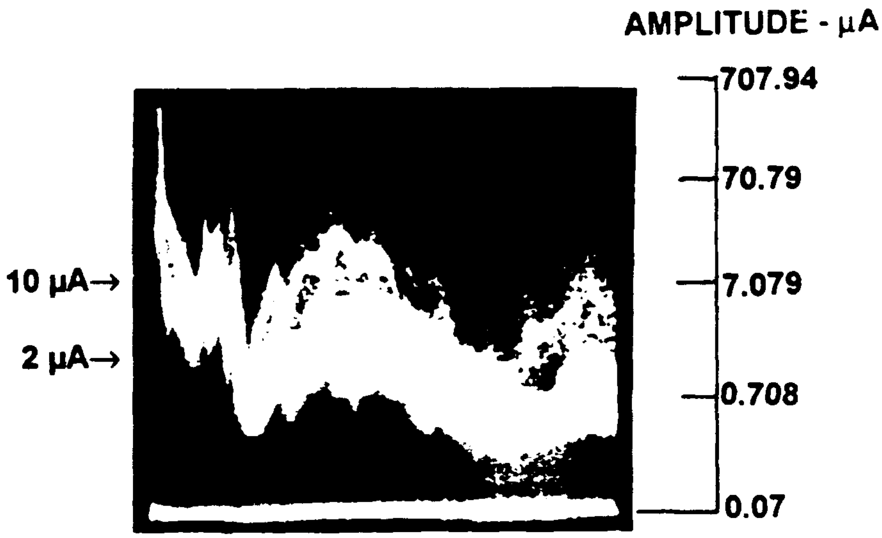


930225 1925
NPS, LAB 419, UPS Input
Inside Barrier, Green Wire/Battery
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -40

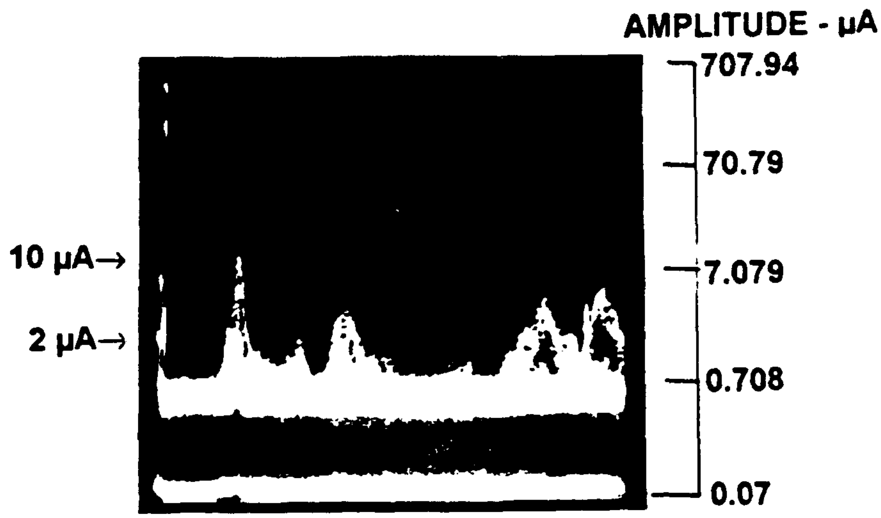


930226 1245
NPS, LAB 419, UPS Input
Outside Barrier, Green Wire/Battery
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -30

Figure 47. Current-Green Wire-Input-Battery Operated

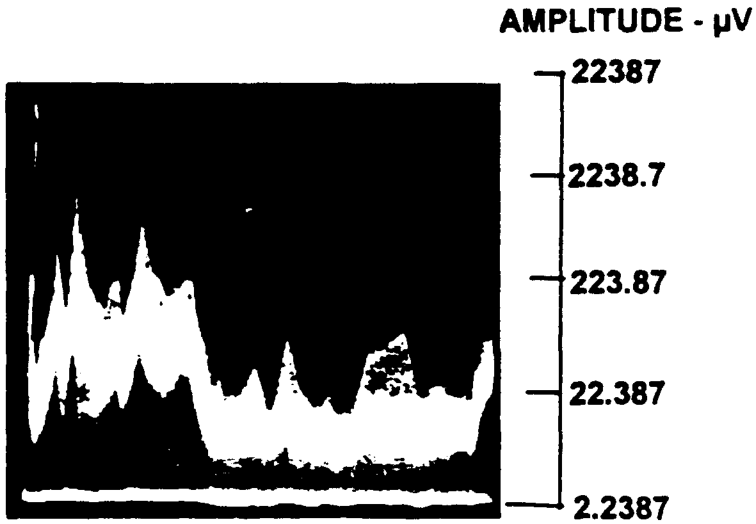


930225 1940
NPS, LAB 419, UPS Output
Inside Barrier, Green Wire/Battery
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -40

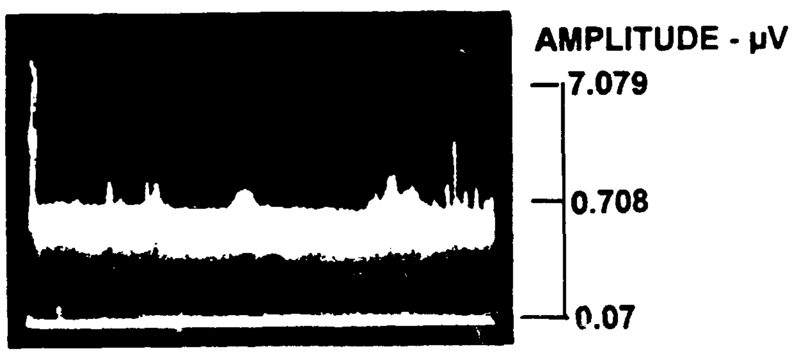


930225 2008
NPS, LAB 419, UPS Output
Outside Barrier, Green Wire/Battery
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
F-70, +10, 0, -40

Figure 48. Current-Green Wire-Output-Battery Operated

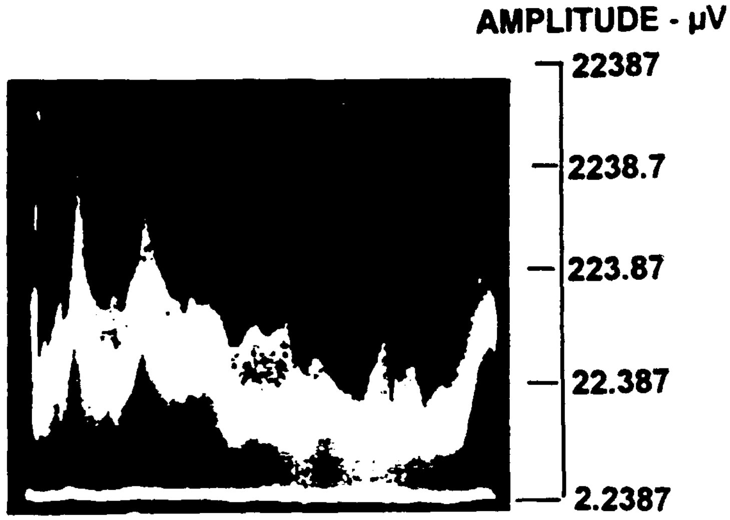


930226 1254
NPS, LAB 419, UPS Input
Inside Barrier, Black-Green Line
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
201D, +10, 0, 0, -30

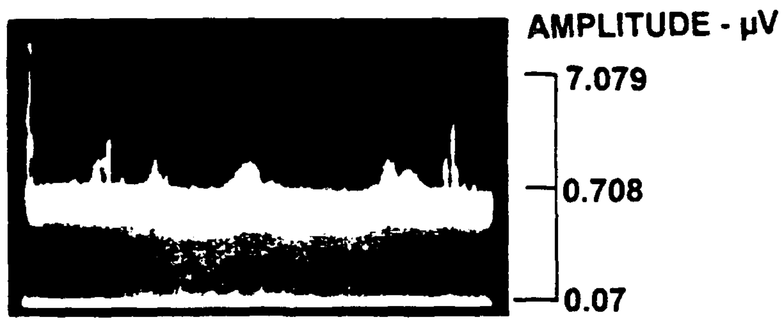


930226 1330
NPS, LAB 419, UPS Input
Outside Barrier, Black-Green Line
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
201D, +10, 0, 0, -60

Figure 49. Voltage Spectrum-Input

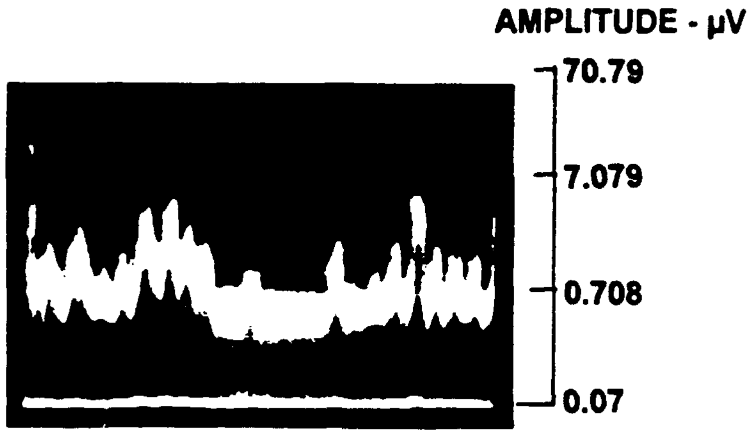


930226 1305
NPS, LAB 419, UPS Output
Inside Barrier, Black-Green Line
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
201D, +10, 0, 0, -30

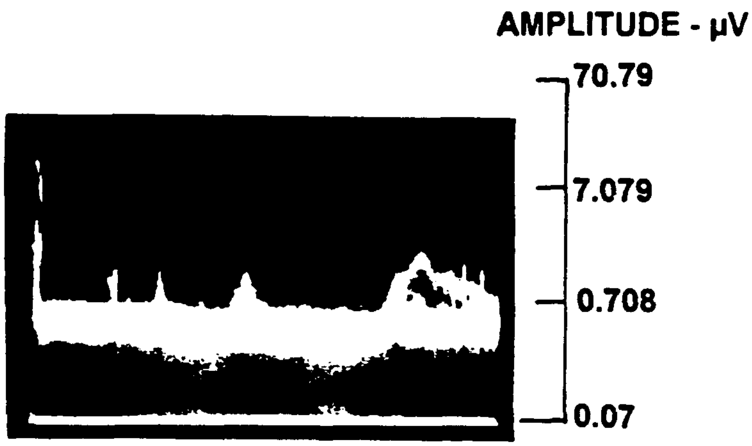


930226 1347
NPS, LAB 419, UPS Output
Outside Barrier, Black-Green Line
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
201D, +10, 0, 0, -60

Figure 50. Voltage Spectrum-Output

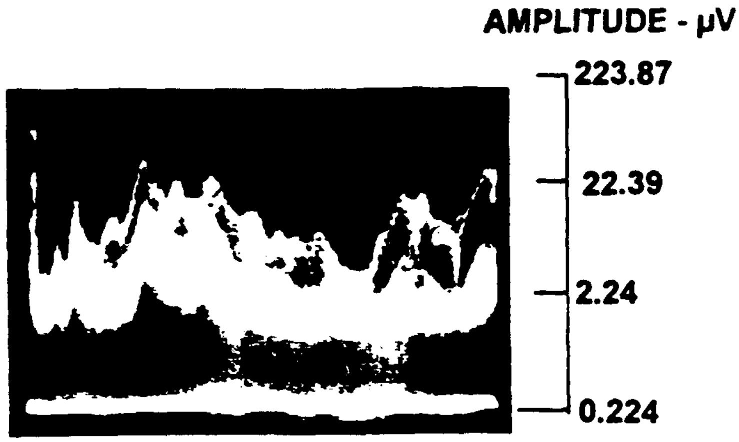


930226 1445
NPS, LAB 419, UPS Input
Inside Barrier, Black-Green /Battery
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
201D, +10, 0, 0, -60

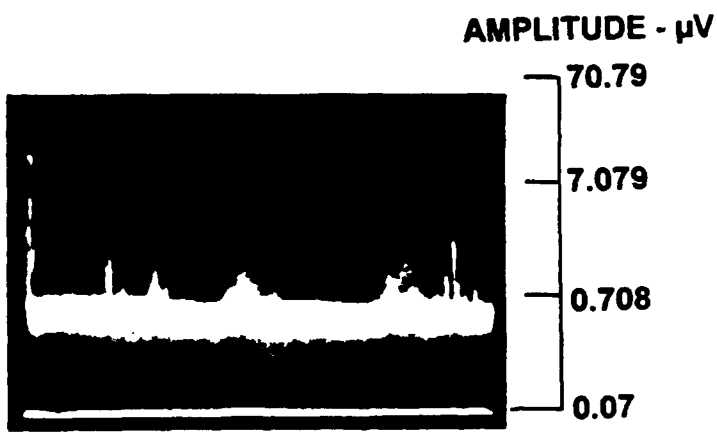


930226 1427
NPS, LAB 419, UPS Input
Outside Barrier, Black-Green/Battery
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
201D, +10, 0, 0, -60

Figure 51. Voltage Spectrum-Input-Battery Operated



930225 1605
NPS, LAB 419, UPS Output
Inside Barrier, Black-Green/Battery
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
201D, +10, 0, 0, -50



930226 1410
NPS, LAB 419, UPS Output
Outside Barrier, Black-Green/Battery
50 MHz, 100 MHz, 30 kHz, 200 ms (LS)
201D, +10, 0, 0, -60

Figure 52. Voltage Spectrum-Output-Battery Operated

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